

Searches for Lepton Flavor Violating Higgs Decay ($H \rightarrow \mu\tau$)

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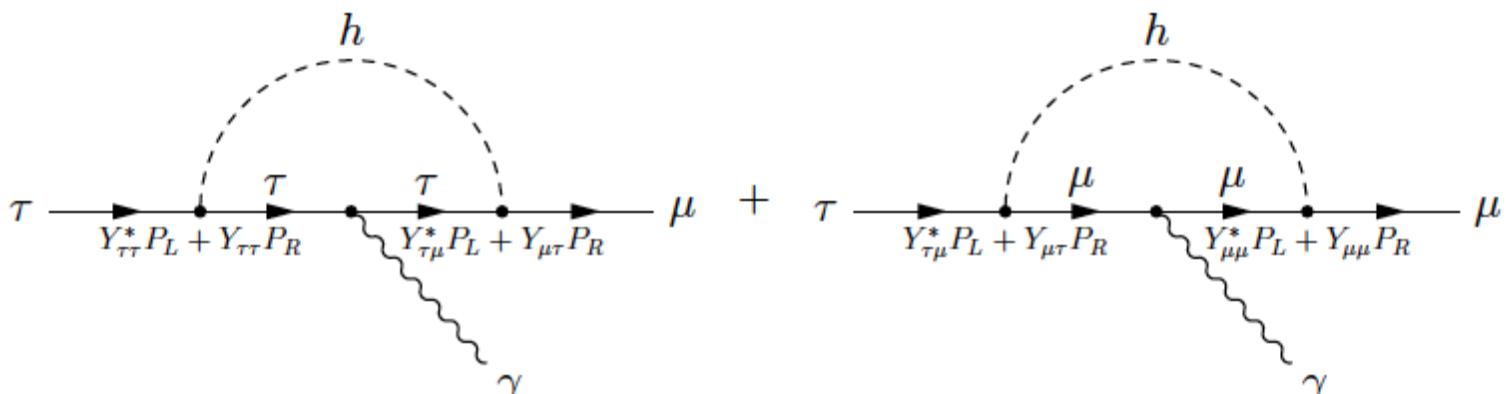
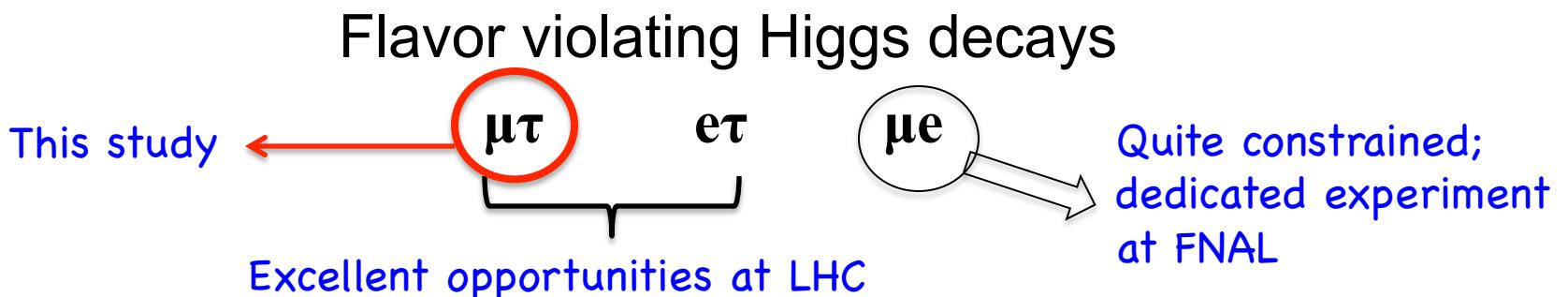
Outline

- Introduction
- Object Definitions
- Trigger Efficiencies
- SM Backgrounds
- Control regions
- Signal regions
- Very preliminary expected limits
- Interpretation of result to Yukawa coupling
- Summary and Outlook

For theory reference: [arXiv:1209.1397](https://arxiv.org/abs/1209.1397)

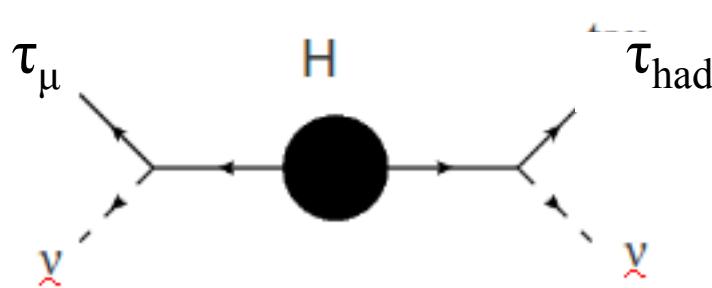
- Search for the Higgs in decay channels that we do not expect in the SM
→ May lead to a striking signal for New Physics

For example:

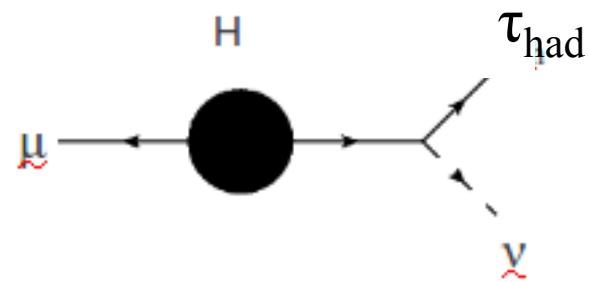


$$\mathcal{L}_Y \supset -Y_{e\mu} \bar{e}_L \mu_R h - Y_{\mu e} \bar{\mu}_L e_R h - Y_{e\tau} \bar{e}_L \tau_R h - Y_{\tau e} \bar{\tau}_L e_R h - Y_{\mu\tau} \bar{\mu}_L \tau_R h - Y_{\tau\mu} \bar{\tau}_L \mu_R h + h.c..$$

- Lepton flavor violation is not permitted by standard model
 - SM Higgs search: $H \rightarrow \tau_h \tau_h$
 - BSM process (in this study): $H \rightarrow \tau_h \mu$ or $H \rightarrow \tau_e \mu$
- BR of up to 10% (for both $H \rightarrow e\tau$ or $H \rightarrow \mu\tau$)
- Larger visible mass
- Predicted by various BSM theories



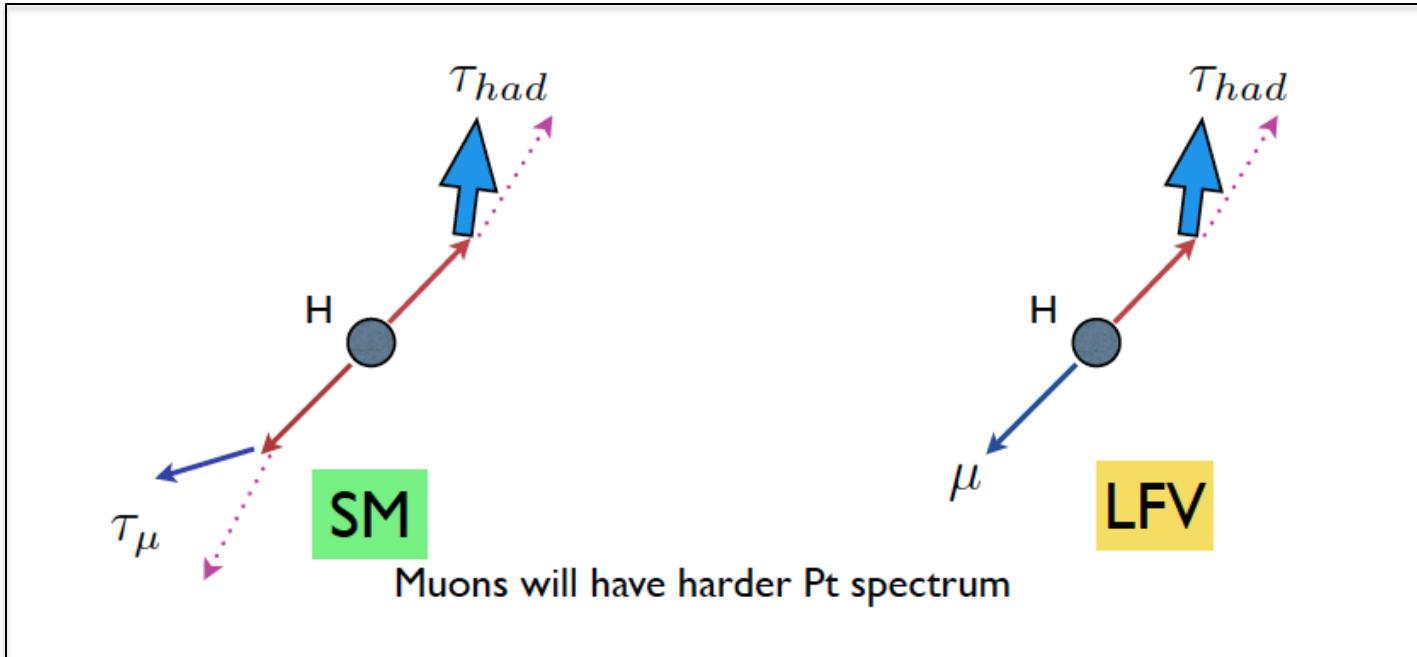
SM process



BSM process

- The limit on flavor violating Higgs decays and puts new constraints on BSM theories

Differences between LFV and SM Higgs



- Harder Muon Pt
- MET Collinear with τ_{had}
- Muon almost back to back with the τ_{had}
- Larger Visible Mass, $M(\mu\tau)$

This study
assumes:
 $M_{Higgs} = 125 \text{ GeV}$
 $BR(H \rightarrow \mu\tau) \leq 0.1$

2 Channels

- $H \rightarrow \tau_e \mu$ and $H \rightarrow \tau_h \mu$

 Split each channel into 0, 1 and 2 jet categories

- 0 and 1 jet categories roughly correspond to **GG** Higgs production
- 2 jet category corresponds to **VBF** Higgs production

$$H \rightarrow \mu_e \tau$$

Basic object selection criteria:

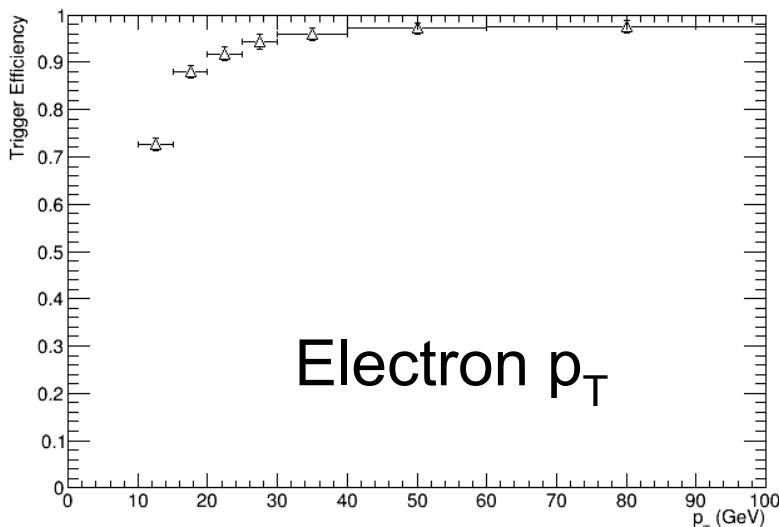
- Muon:
 - $p_T > 25\text{GeV}$
 - $|\eta| < 2.1$
 - POG ID Tight
 - $\text{PFRellso} < 0.15$
- Electron:
 - $p_T > 10\text{GeV}$
 - $|\eta| < 2.3$
 - POG ID Tight (no MVA ID)
 - $\text{PFRellso} < 0.15$
- PFJets (L1L2L3 corrected)
 - $p_T > 30\text{GeV}$
 - $|\eta| < 4.7$
 - ID requirements
 - b-tag CSV medium working point (\rightarrow b-Veto)
- PFMET
 - TypeI - corrected
 - MET x,y shift correction applied

PileUp-Reweighting on MCs applied
Electron/Muon ID&ISO efficiencies corrected(TnP)

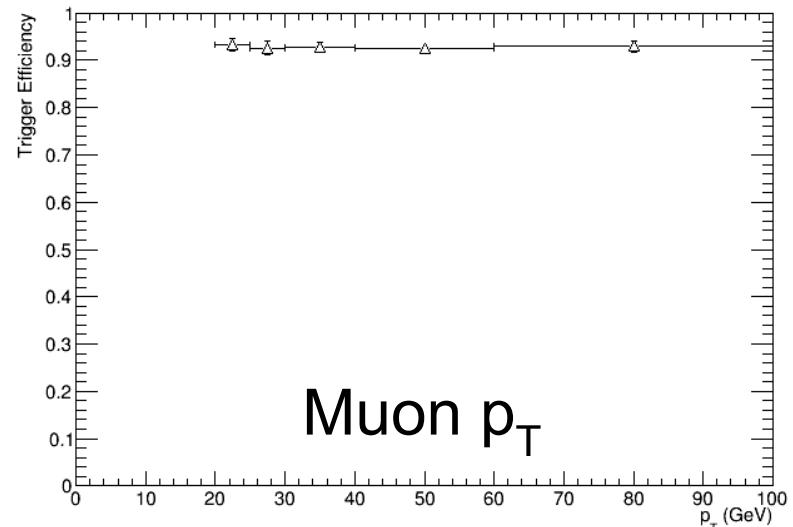
- Used Trigger:

HLT_Mu17_Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL

- Electron(Muon) leg is measured using SingleMu(Electron)-Triggered data sample



Electron p_T



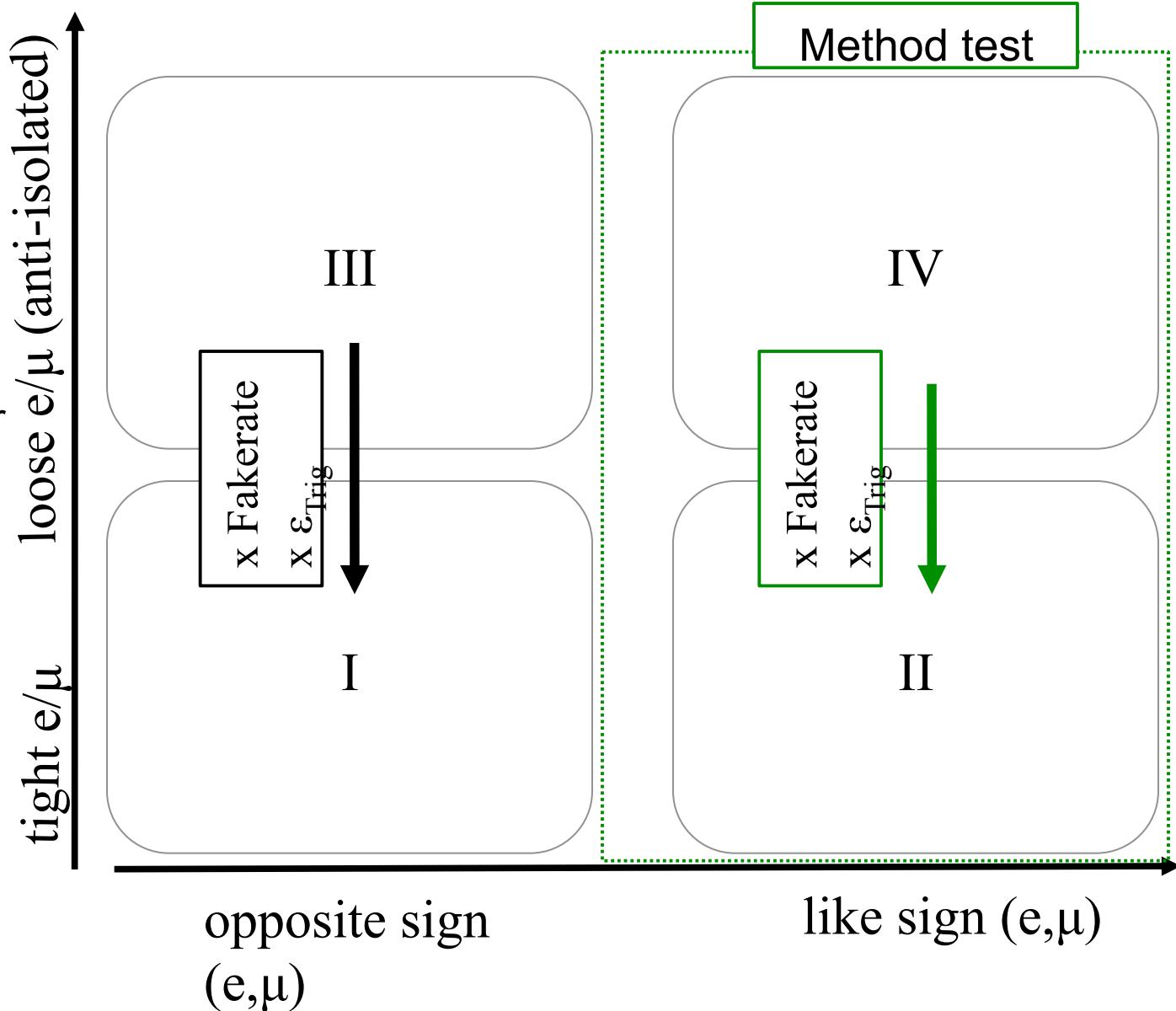
Muon p_T

- MC is corrected for Trigger-efficiency:

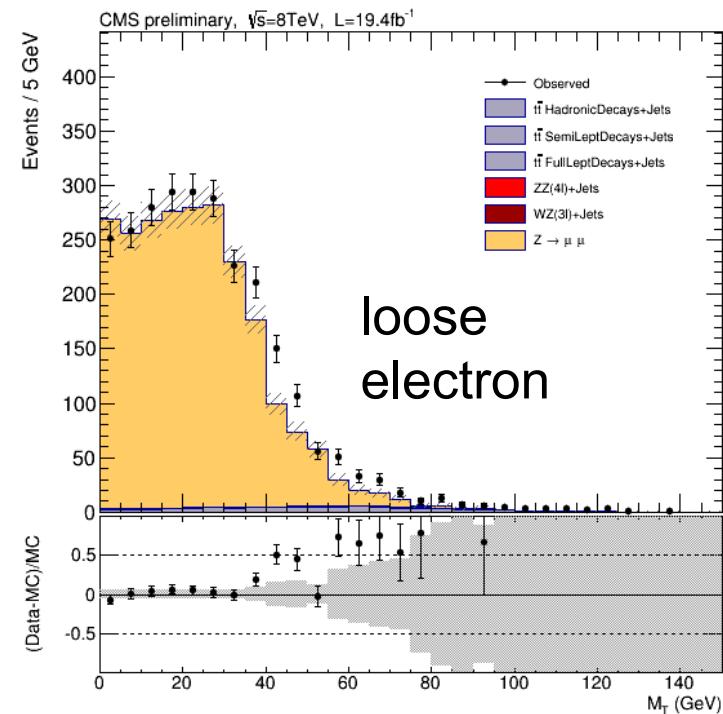
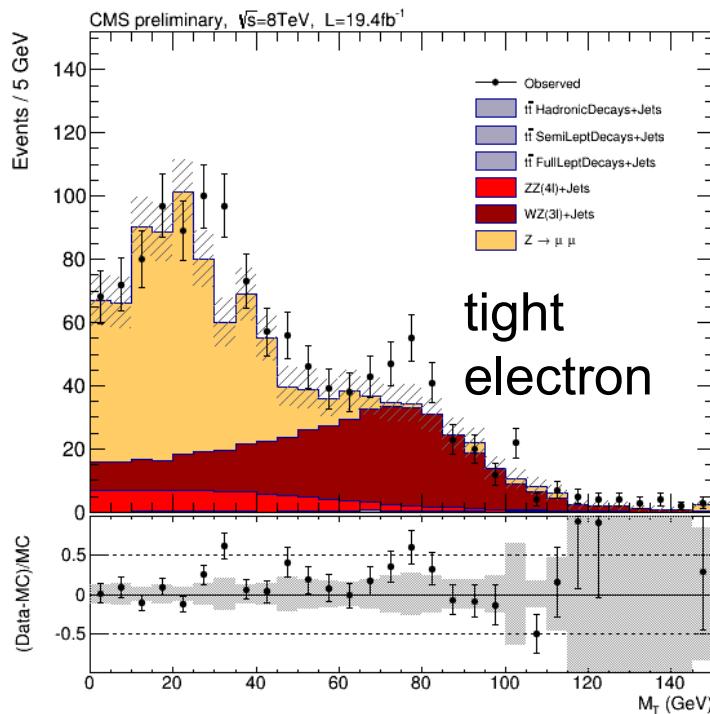
$$\epsilon_{\text{Trig}} = \epsilon_{\text{EleTrig}}(p_T, \eta) \times \epsilon_{\text{MuTrig}}(p_T, \eta)$$

- Two types of backgrounds to be considered
- Irreducible:
 - $Z \rightarrow \tau\tau \rightarrow lluu$
 - $WW \rightarrow lluu$
 - $tt \rightarrow lluubb$
 - $tW \rightarrow llub$
- Reducible:
 - $W + \text{Jets/QCD Multijets} + \text{fake-lepton}$
 - $W+\gamma^{(*)} + \text{Jets}$
- + SM Higgs, other Di-Boson, more rare processes

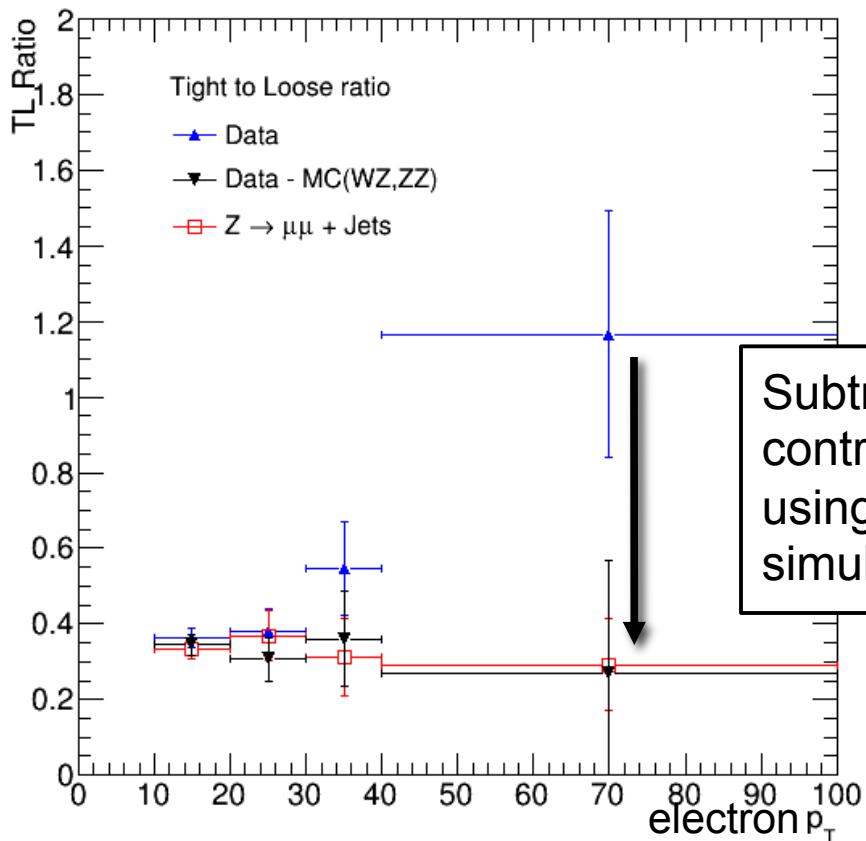
- ❑ Idea: use anti-isolated electron/muon events to predict signal shape
- ❑ Apply fakerate and correct for Trigger efficiency (SingleLeptonTriggered Dataset)
- ❑ Measure fakerate in an independent dataset



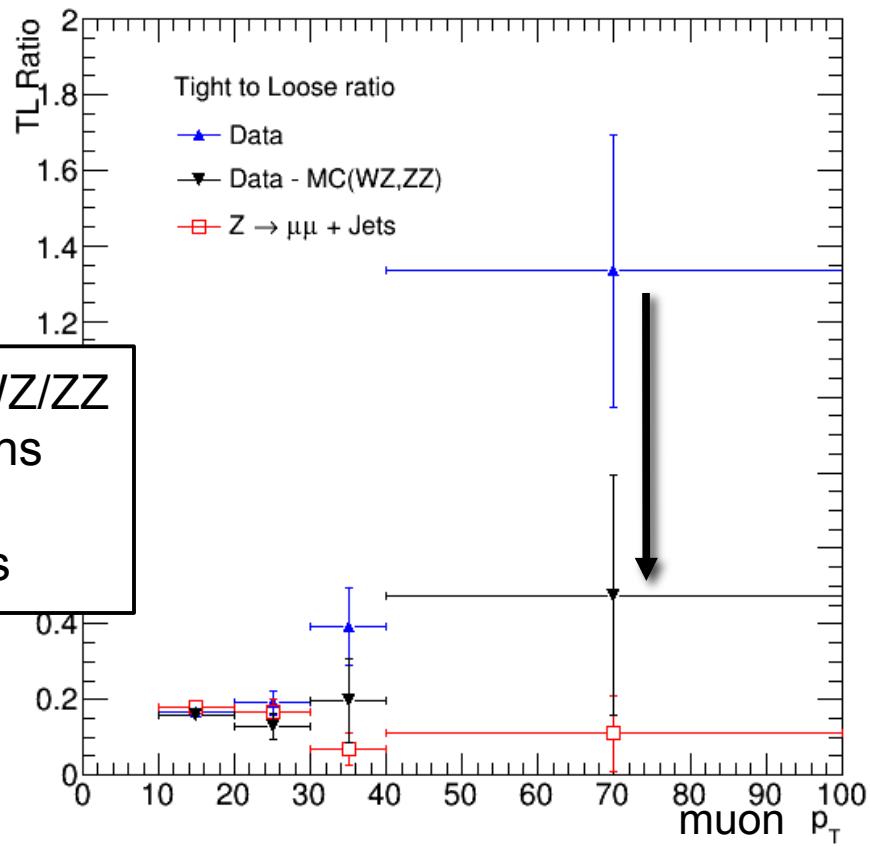
- Measure fakerate in $Z \rightarrow \mu\mu + \text{fake electron/muons events}$
 - $M(\mu\mu) = M_Z +/- 15\text{GeV} + \text{electron (loose/tight isolation)}$
 - To suppress Di-Boson contribution :
 $M_T(e, \text{MET}) < 30\text{ GeV} \& \text{MET} < 40\text{ GeV}$



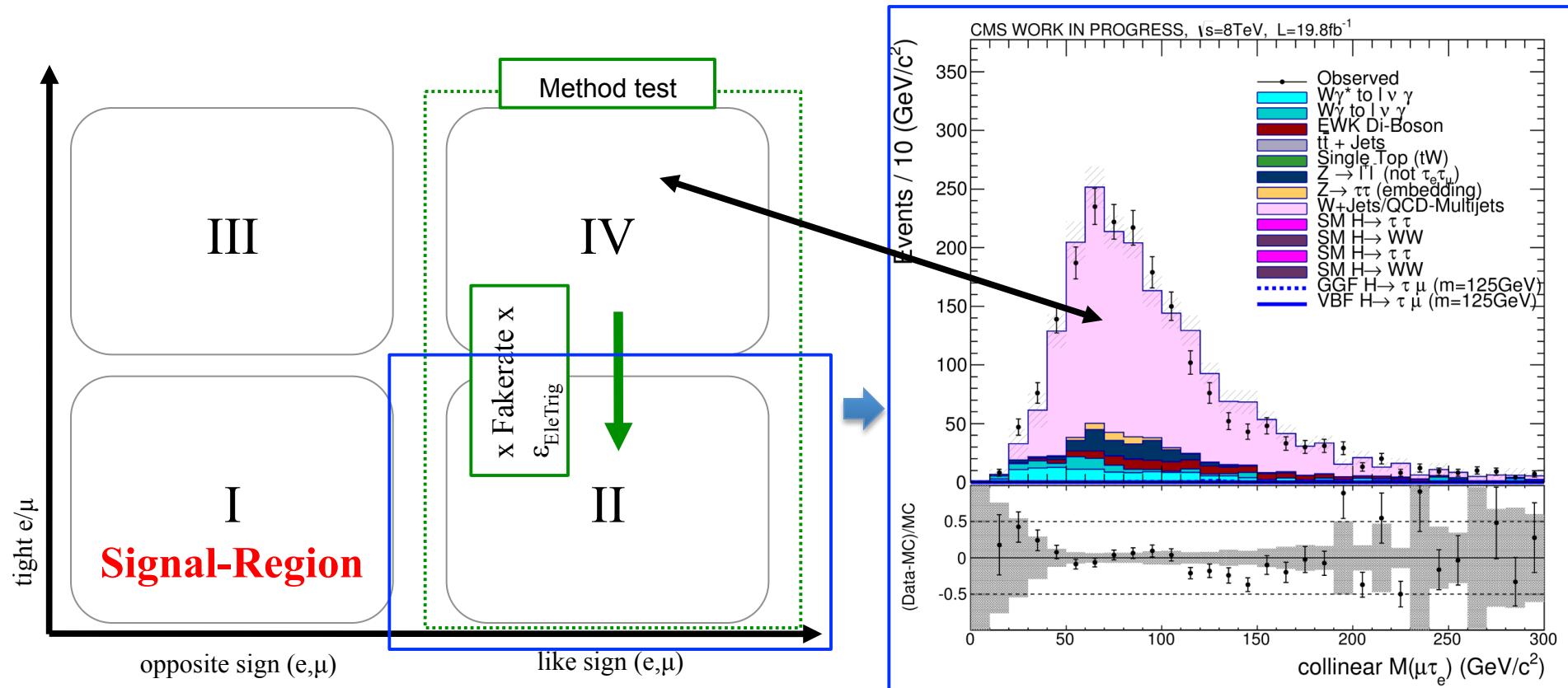
Fakerate measurement



Subtract WZ/ZZ
contributions
using MC
simulations



- ❑ Preliminary fakerate is applied as function of electron/muon p_T and η

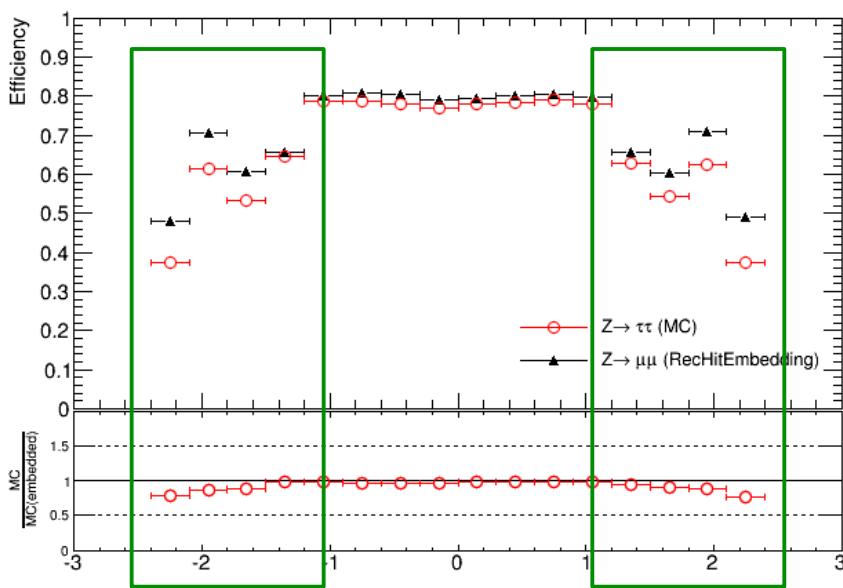


- ❑ Collinear mass in the 0-jets Like-Sign category is nicely predicted by the fakerate method
- ❑ Same was observed for 1-jet and 2-jet categories

Z-> $\tau\tau$ background

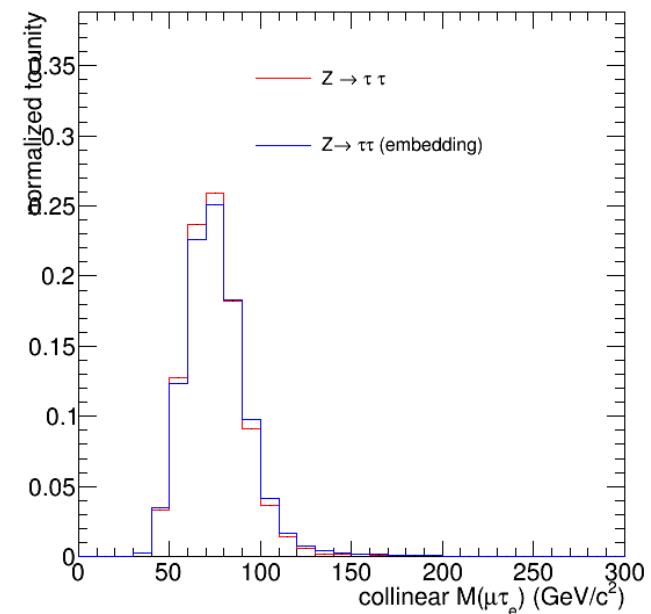
- ❑ Z $\rightarrow \tau\tau$ background is estimated using the [embedding method](#)
- ❑ Normalization is taken from MC simulations
- ❑ Shape is taken from data using Z $\rightarrow \mu\mu$
- ❑ and replacing both muons with simulated τ 's

- ❑ Electron ID/ISO efficiency differences corrected at high η with respect to MC



Z $\rightarrow \tau\tau$ simulations

- ❑ PFE embedded samples are weighted by a correction factor $\varepsilon(p_T, \eta)$
- ❑ Muon: efficiency correction factors are compatible with unity



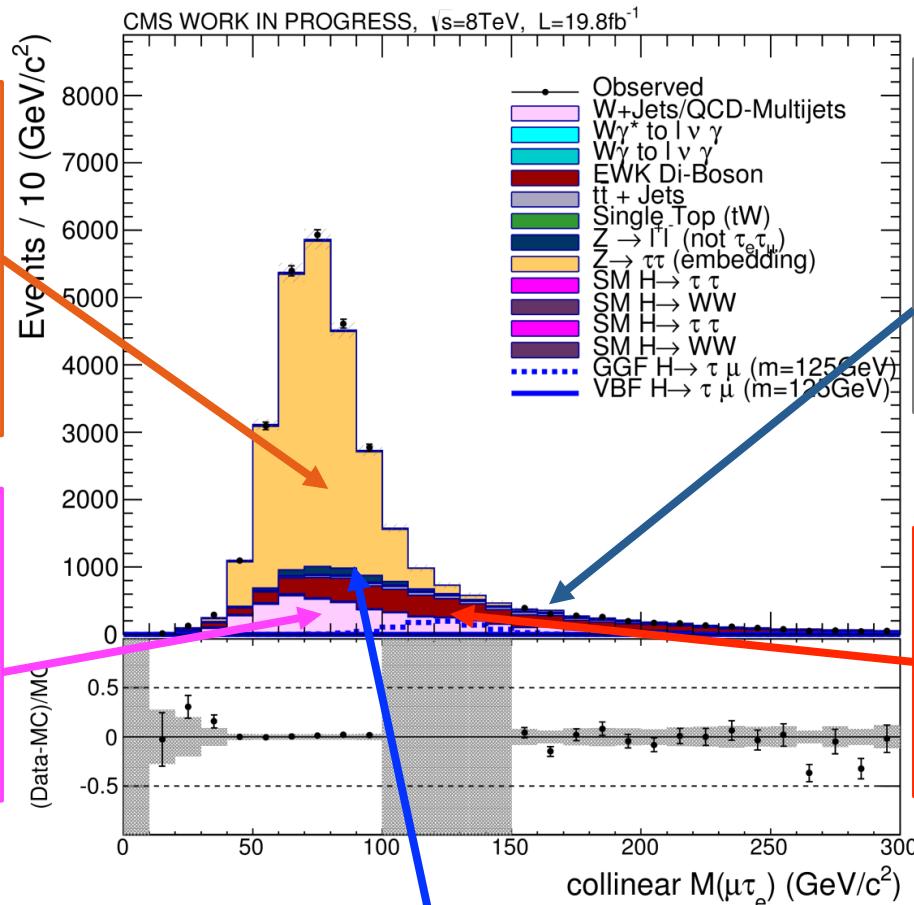
Background summary

$Z \rightarrow \tau\tau$:

- Normalization from MC simulation
- Shape: PF Embedded sample

W+Jets/QCD Multijets:

- Fakerate Method
- Shape from Anti-isolated lepton events



$t\bar{t}$:

- Shape from MC simulations
- Normalization from control region (to be done!)

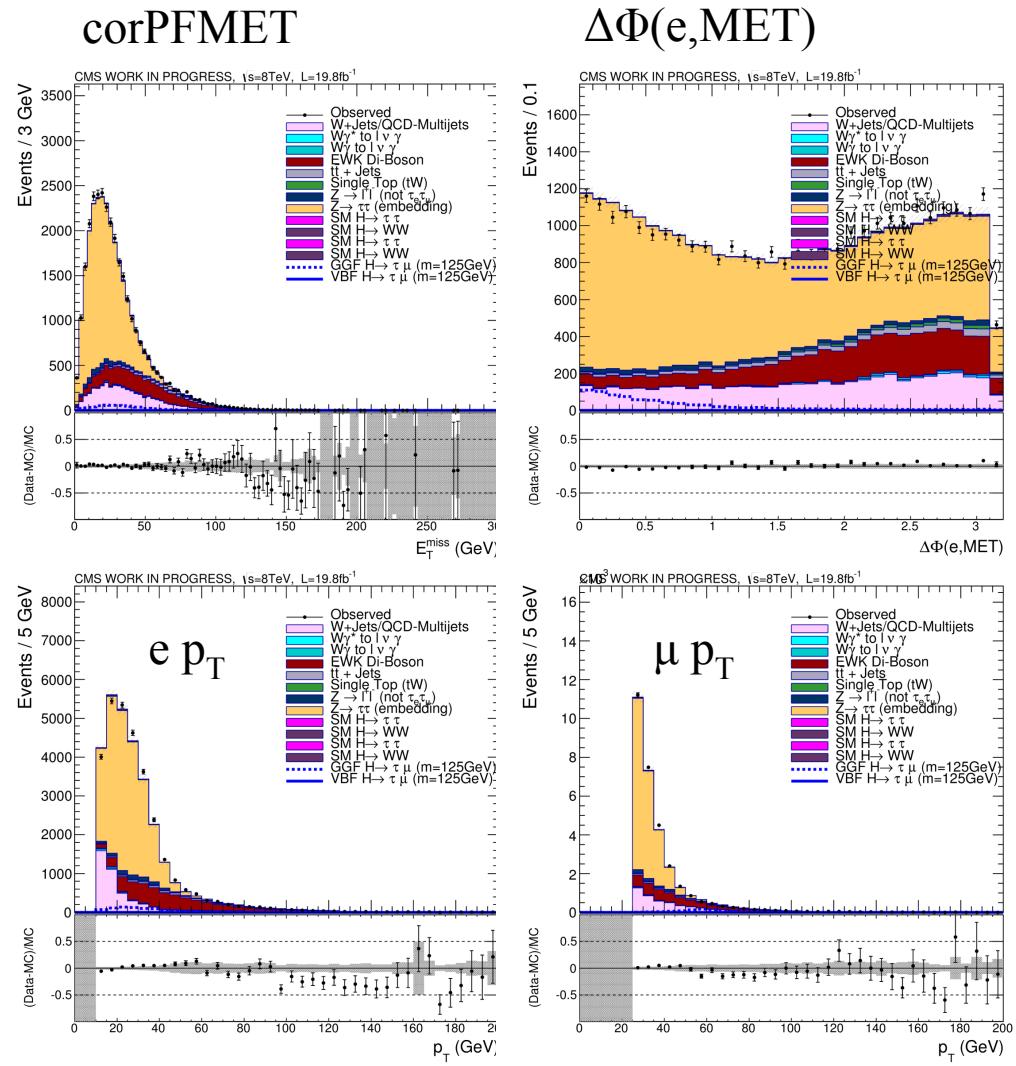
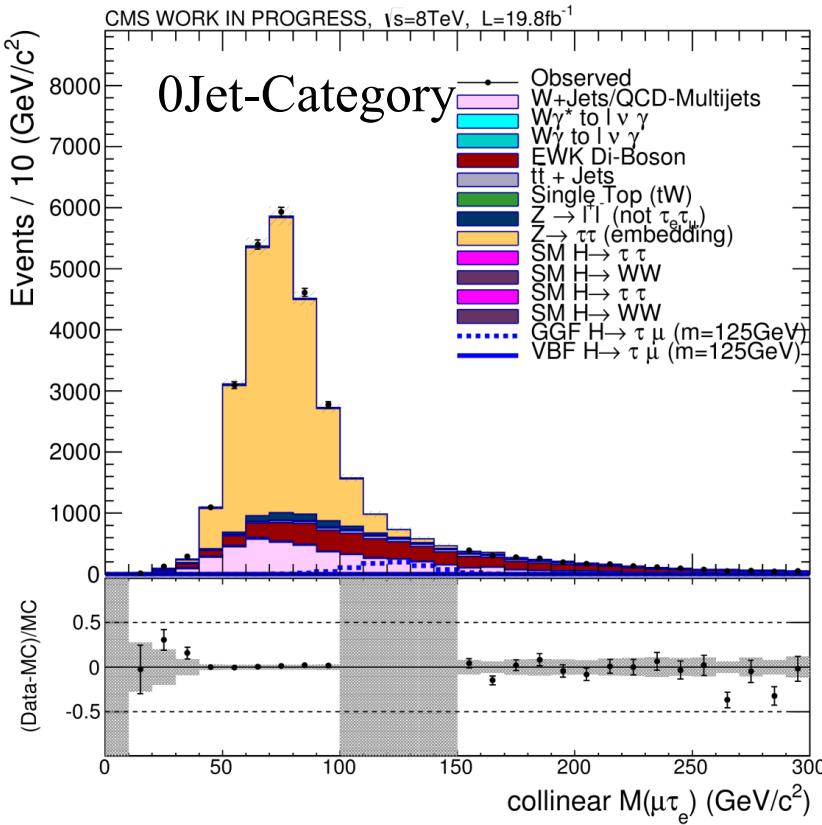
WW+Jets:

- Normalization(NLO) and shape from MC simulations

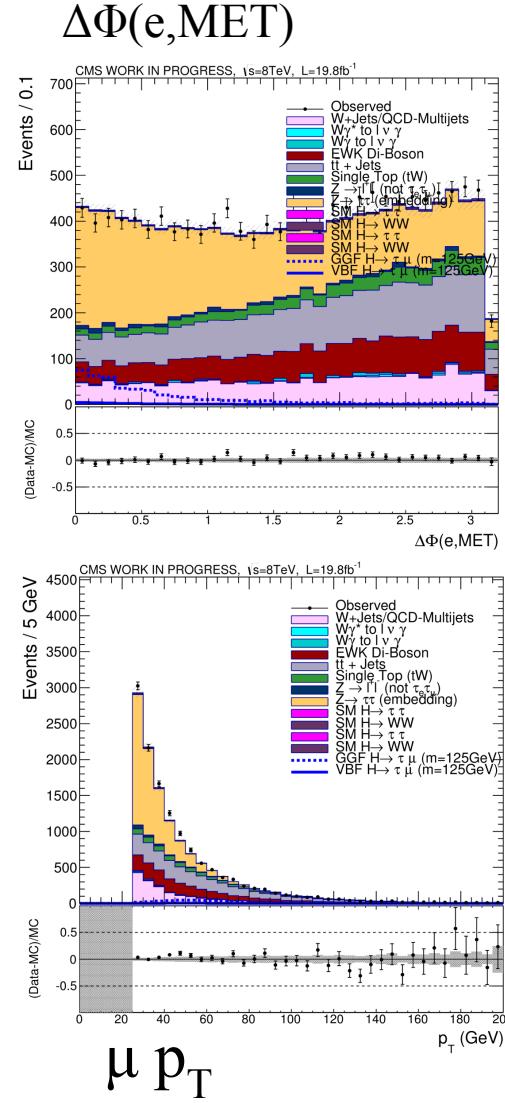
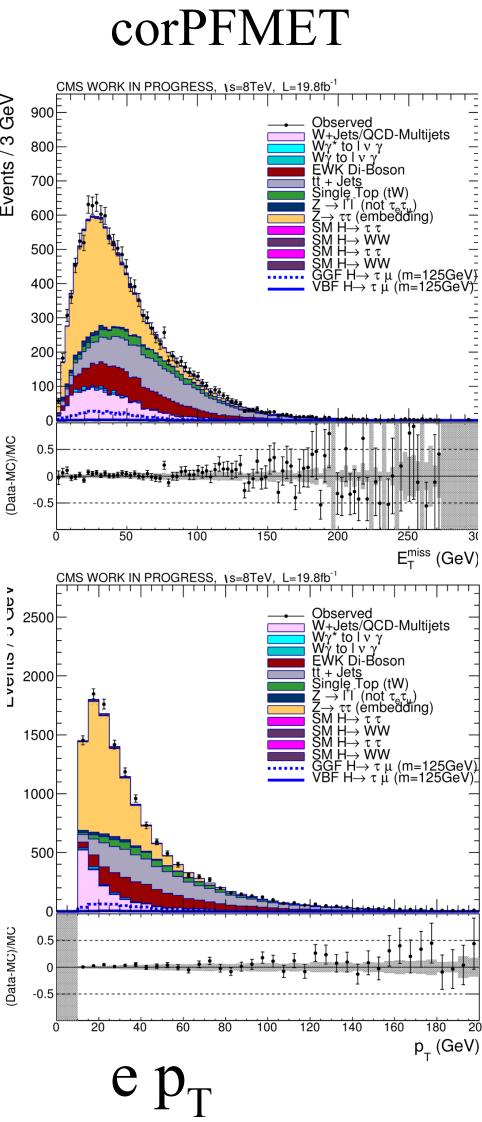
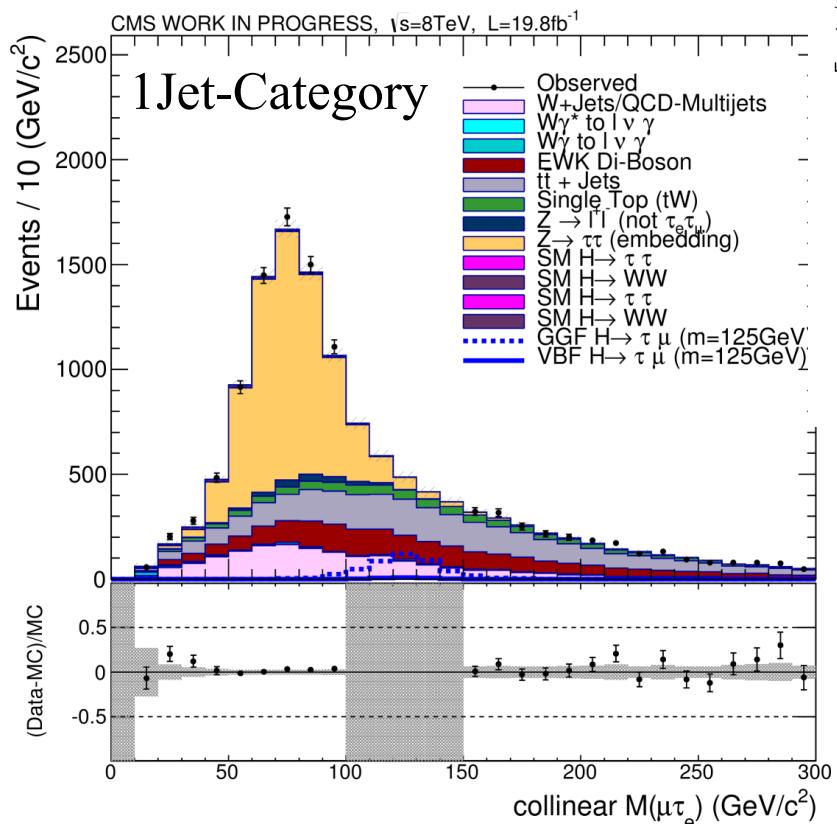
Wjets+gamma(*), SingleTop,...:

- Normalization and shape from MC simulation

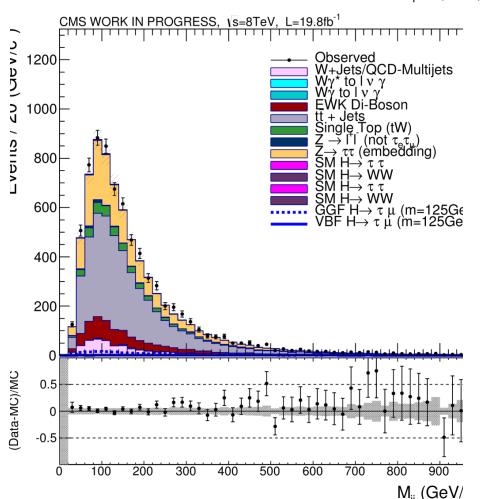
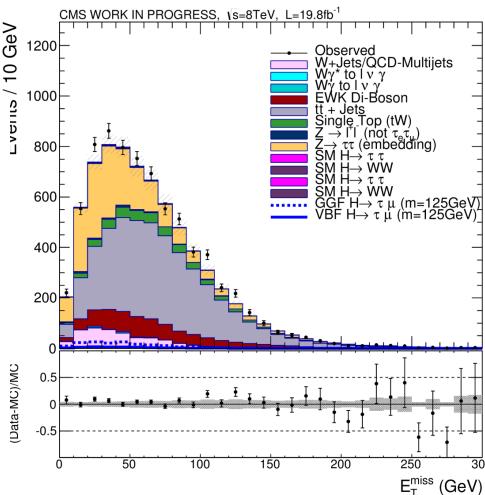
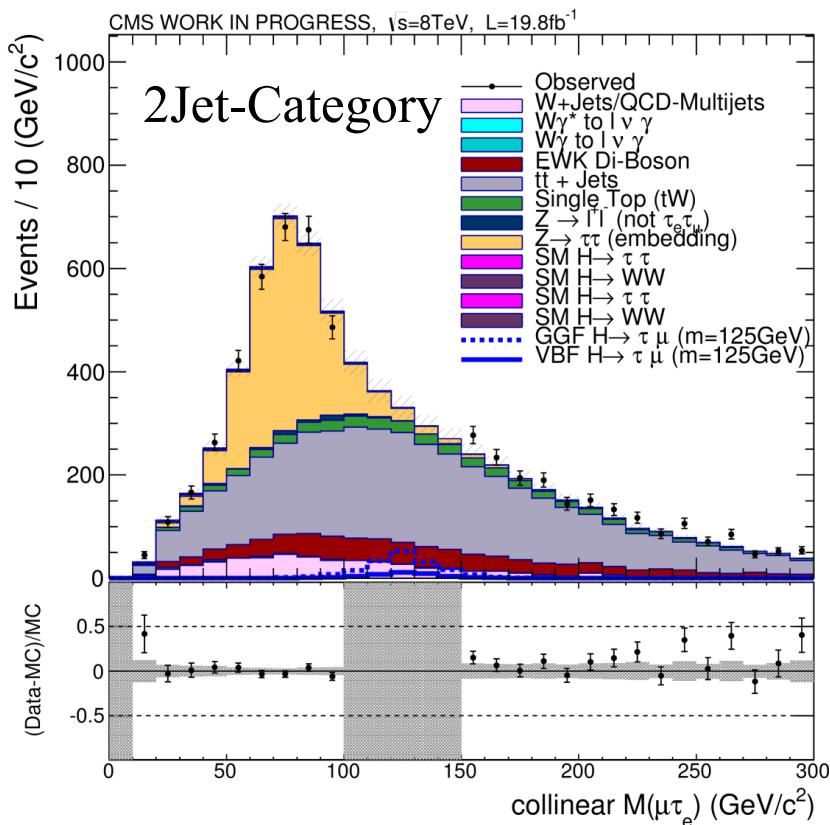
□ Baseline selections



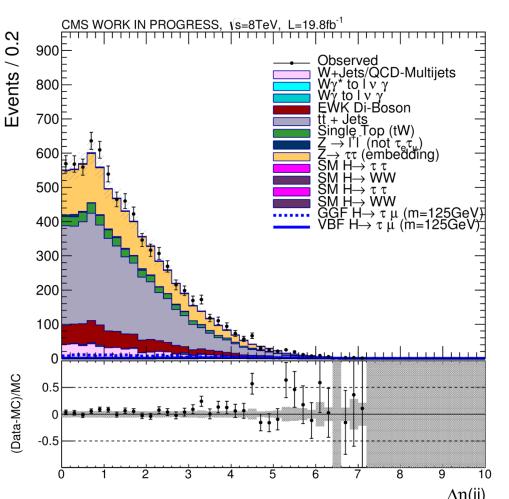
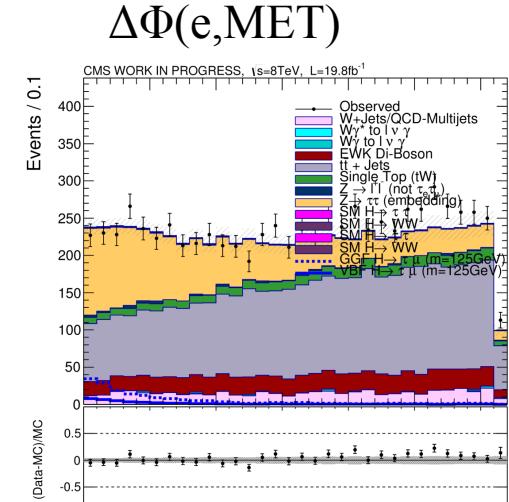
Backgrounds: 1-jet



Backgrounds: 2-jet

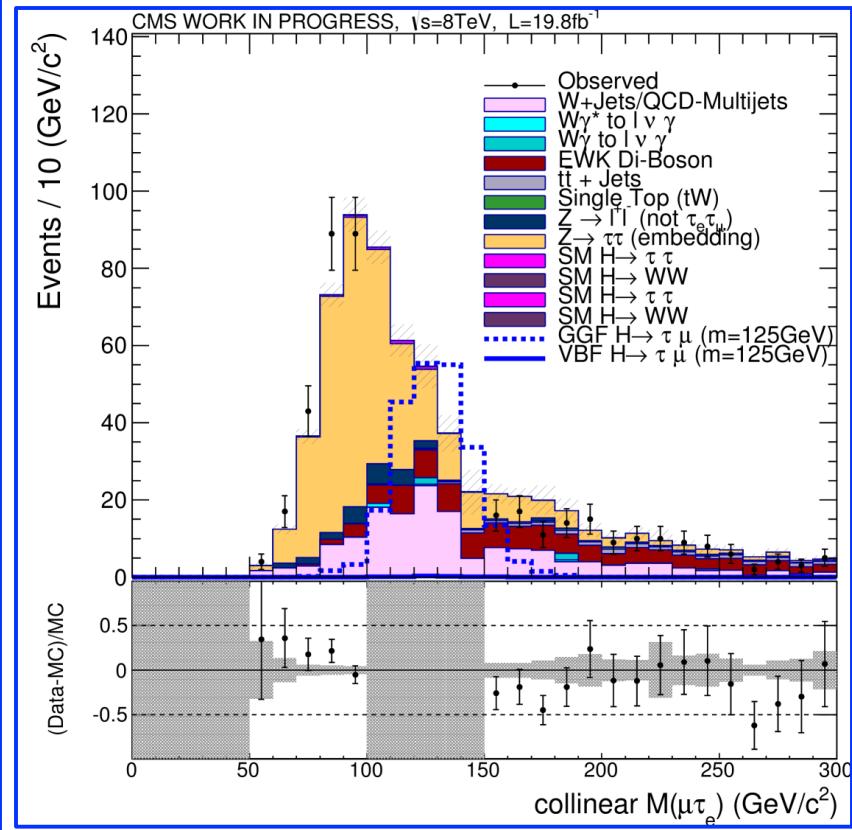
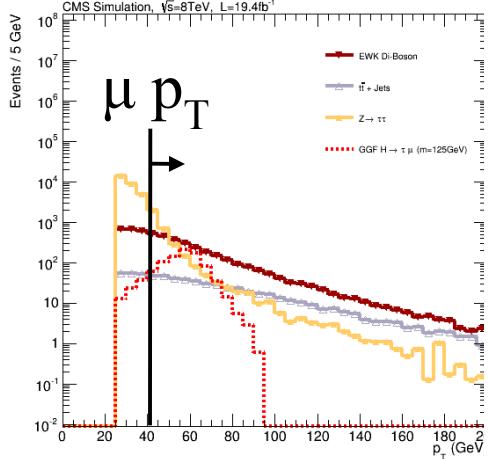
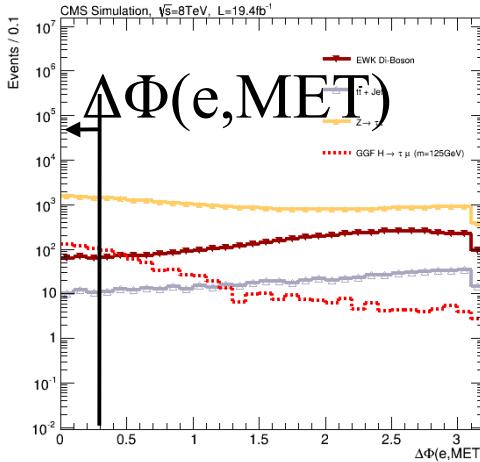


mass(j1j2)



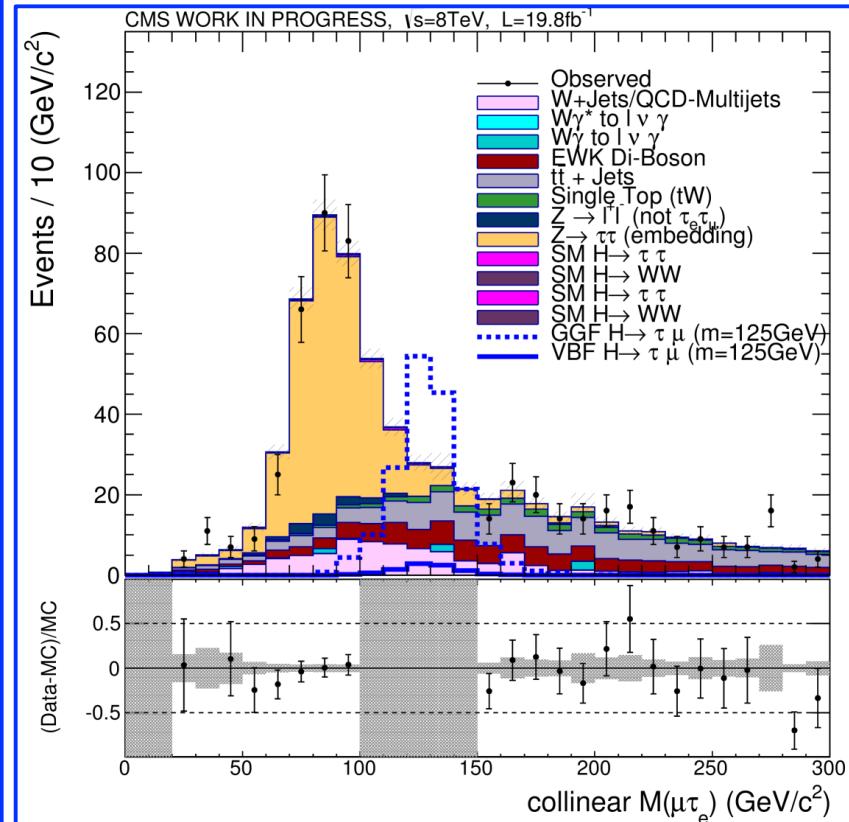
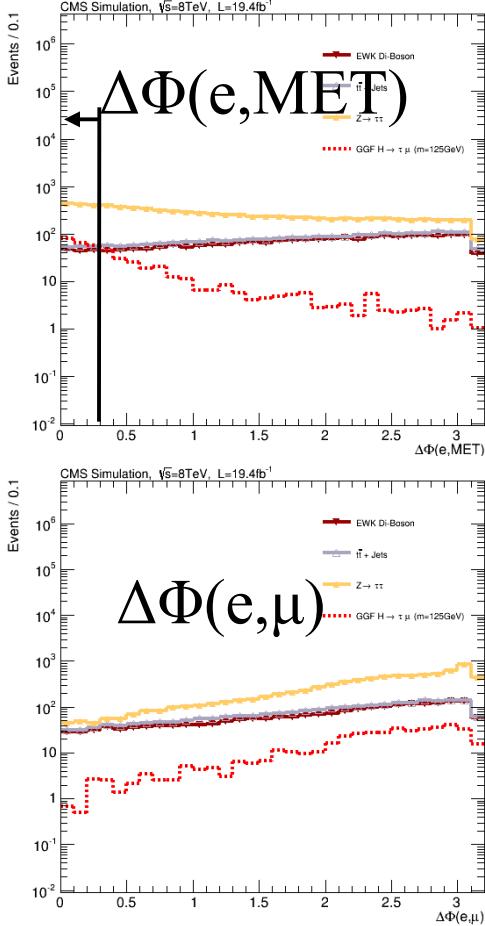
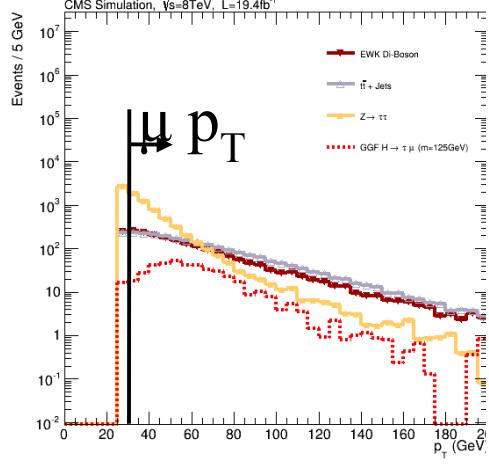
Signal region: 0 jet

- Baseline+
 - Njets=0
 - $p_T(\mu) > 40 \text{ GeV}$
 - $\Delta\Phi(e, \text{MET}) < 0.3$
 - $\Delta\Phi(e, \mu) > 2.7$



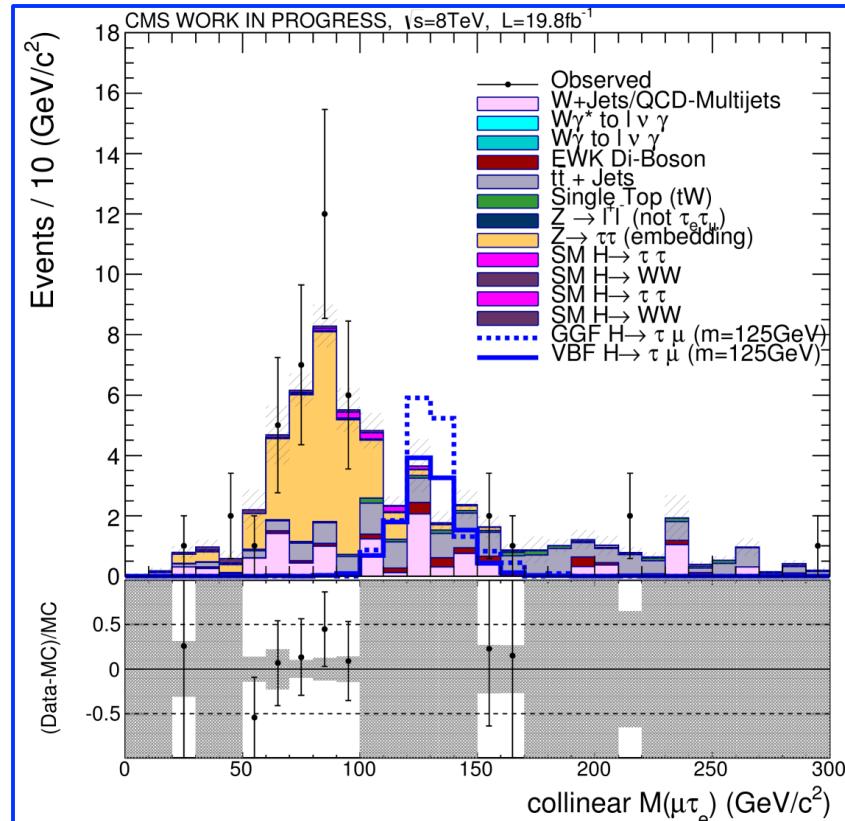
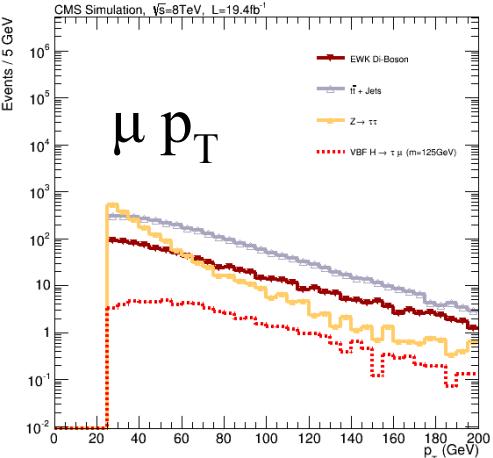
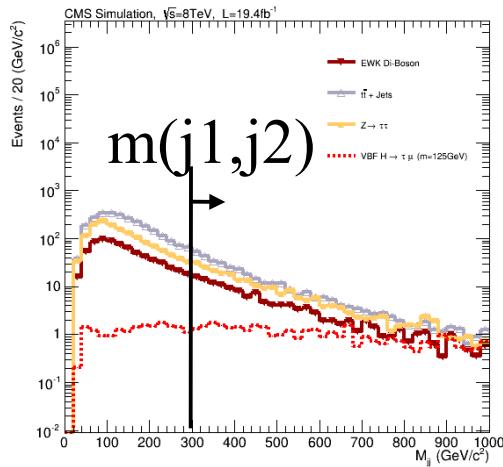
Signal region: 1 jet

- Baseline+
- Njets==1
- $p_T(\mu) > 30 \text{ GeV}$
- $\Delta\Phi(e, \text{MET}) < 0.3$



Signal region: 2 jet

- Baseline+
 - Njets=2
 - $M_{jj} > 300 \text{ GeV}$
 - $\Delta\eta(jj) > 3$
 - $\eta_1 * \eta_2 < 0$
- $p_T(\mu) > 25 \text{ GeV}$
- $\Delta\Phi(e, \text{MET}) < 0.3$



$$H \rightarrow \mu_h \tau$$

Basic selections:

Trigger

- IsoMu24

Main differences w.r.t. H2Tau ($\mu\tau$):

- Trigger / Muon p_T cut
(more energetic muon
allows to use
SingleMuon)
- Muon M_T reversed!
(Only one neutrino
collinear with tau →
opposed to the muon)

Vetos

- MuVetoPt5IsoldVtx
- EvtetoCicTightIso
- Require Muon/Tau
opposite sign

Muon

- $p_T > 30 \text{ GeV}$
- $|\eta| \leq 2.1$
- $D_Z < 0.2$
- $\text{RelPFIsoDB} < 0.12$
- PFIDTight

Tau

- $p_T > 35 \text{ GeV}$
- $|\eta| < 2.3$
- AntiElectronLoose
- AntiMuonTight2
- DecayFinding
- TightIso3Hits

Jets

- 0,1, and 2 jet
requirements for
each of the 3 τ_h/μ channels

All basic selection criteria +

0-jet:

- $\mu p_T > 45 \text{ GeV}$
- $\tau p_T > 35 \text{ GeV}$
- $\Delta\Phi(\tau, \mu) > 2.7$
- Transverse mass(μ ,MET) $< 50 \text{ GeV}$

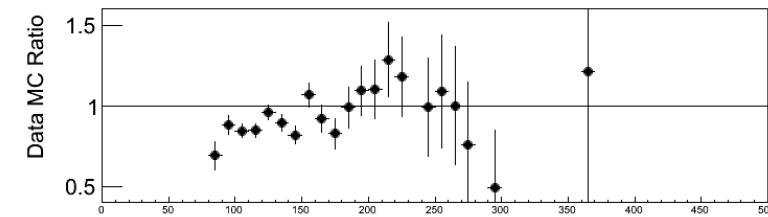
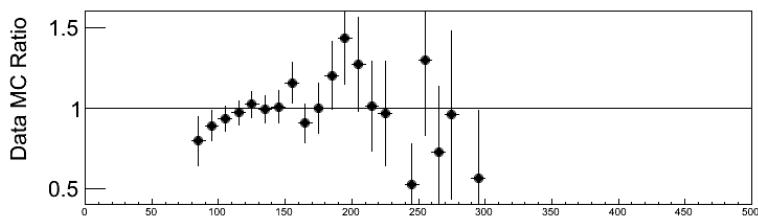
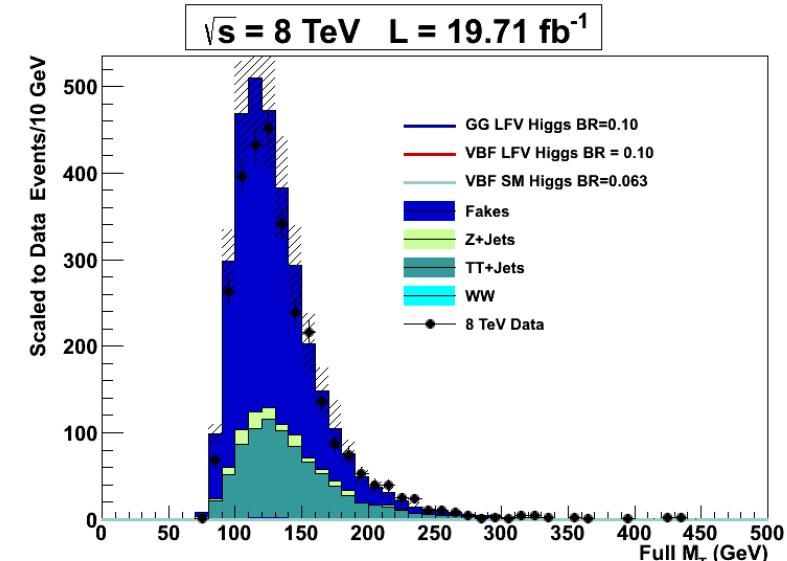
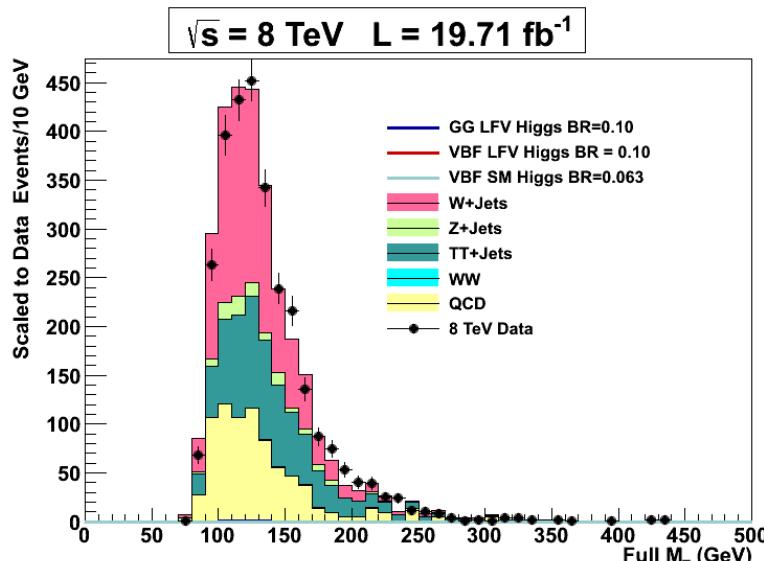
1-jet:

- $\mu p_T > 35$
- $\tau p_T > 40$
- Transverse mass(τ ,MET) < 35

2-jet:

- $\tau p_T > 40$
- Transverse mass(τ ,MET) < 35
- Dijet $|\Delta\eta| > 3.5$
- Dijet Mass > 550

W+Jets background: Fake rate validation



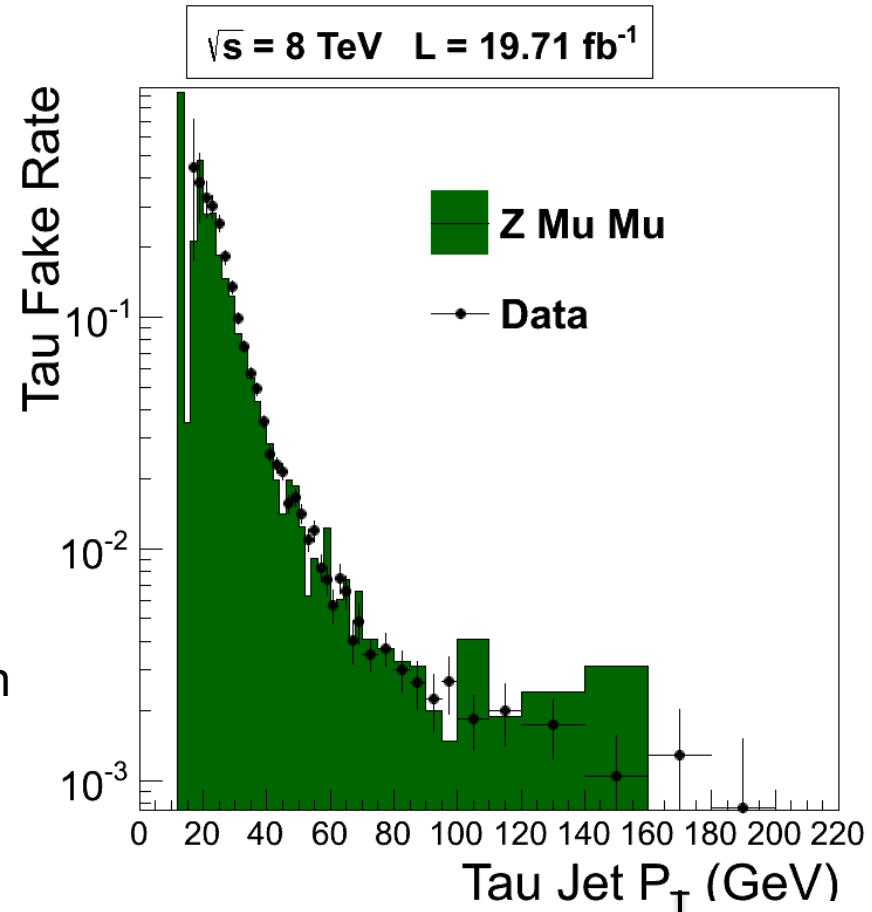
Compare W+jets Monte Carlo and data driven QCD to fake rate method in fakes CR

- Preselection cuts
- μ and τ have same sign
- Transverse mass: $M_T(\mu, \text{MET}) > 70 \text{ GeV}$

Systematic uncertainty: 30%

VBF Fakes estimation

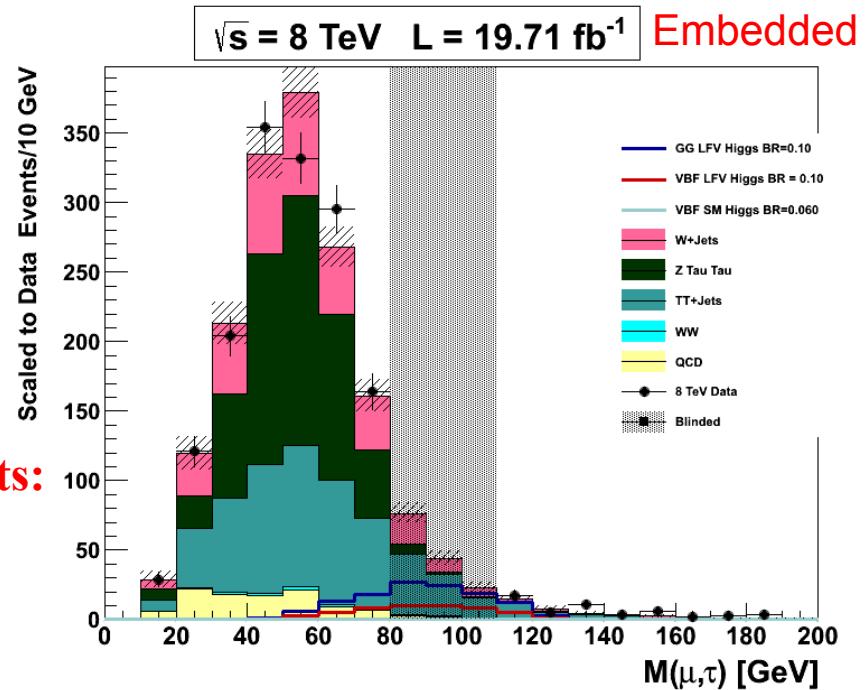
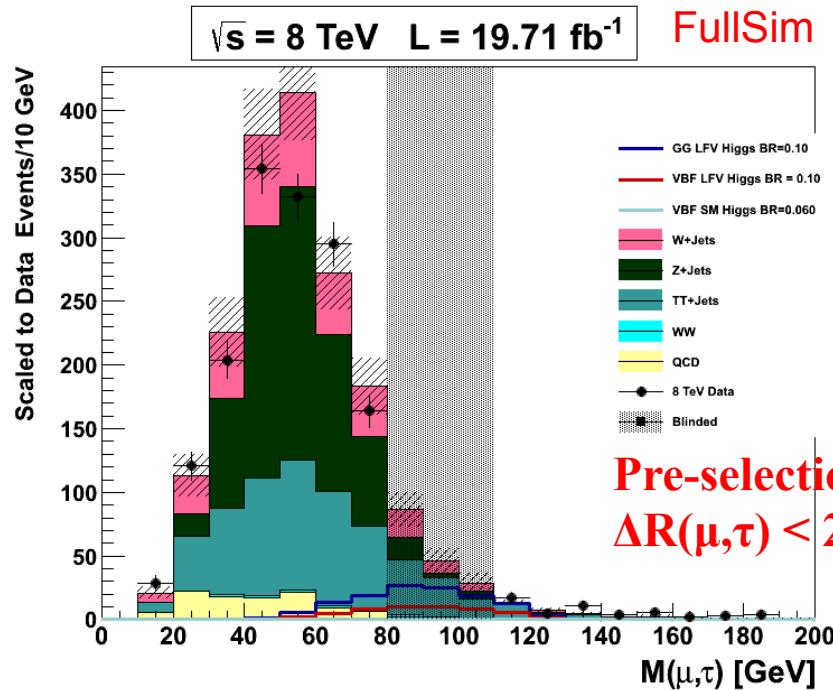
- Select events with two μ 's
- Estimate τ fake rate (f_τ) by computing the fraction of events that pass tau ID but not tau ISO
 - Id cuts:
 - AntiElectronLoose
 - AntiMuonTight2
 - DecayFinding
 - Isolation cut:
 - TightIso3Hits
 - Use data sample fake rate distribution



- Invert tau isolation in data sample to enter fakes-rich region and weight events by a factor of $f_\tau/(1-f_\tau)$
 - Gives shape and yield of “fake” tau events
 - This group of events is dominated by W+jets and QCD

Z-> $\tau\tau$ optimization

- Z+Jets background significantly populated by Z- $\tau\tau$ events
- Benefit from H2Tau (SM) “PF” embedded samples
- Shape is taken from data using Z -> $\mu\mu$ and replacing both μ 's with simulated τ 's

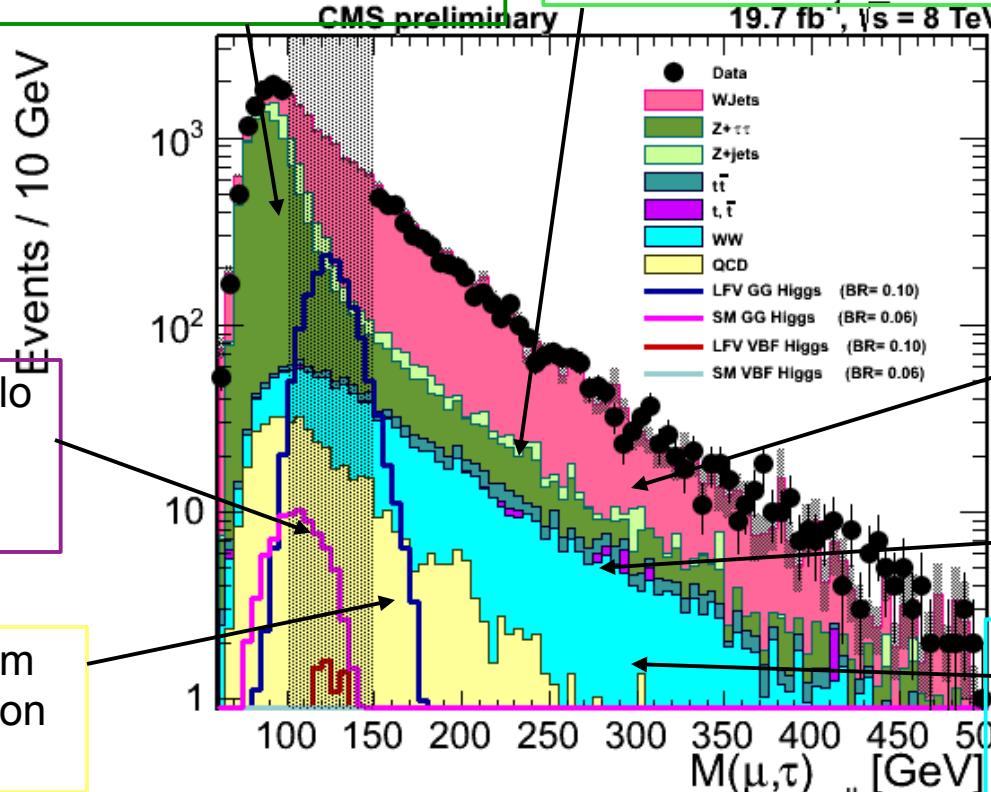


- The embedded sample looks identical to the fullsim sample

0-jet background

Z->tau/tau: (embedded data samples for shape,
DY + (1,2,3,4) jet samples for normalization

Z+jets (other):
Monte Carlo used for
shape and normalization

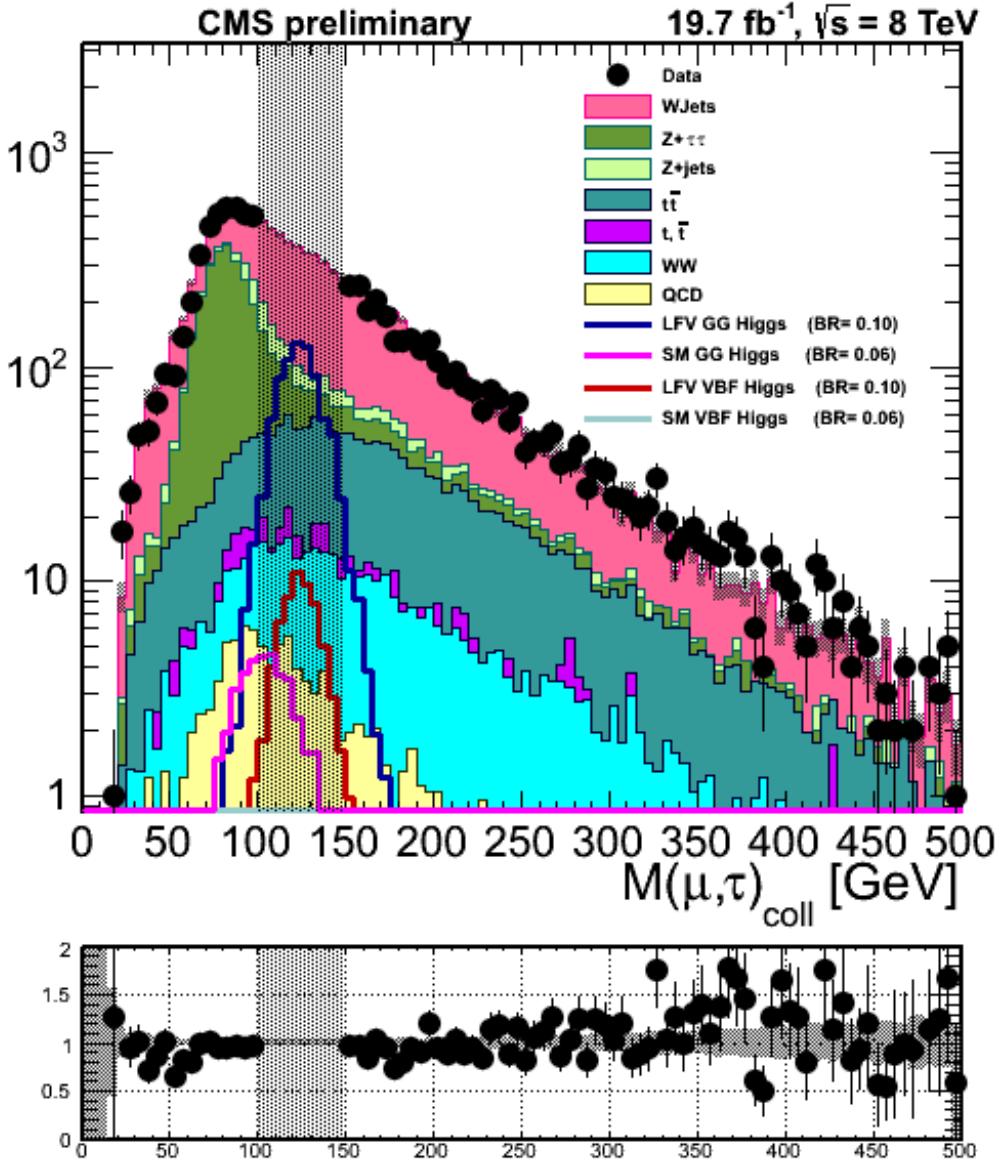


1-jet background

- Backgrounds are determined in the same general way as the 0-jet backgrounds

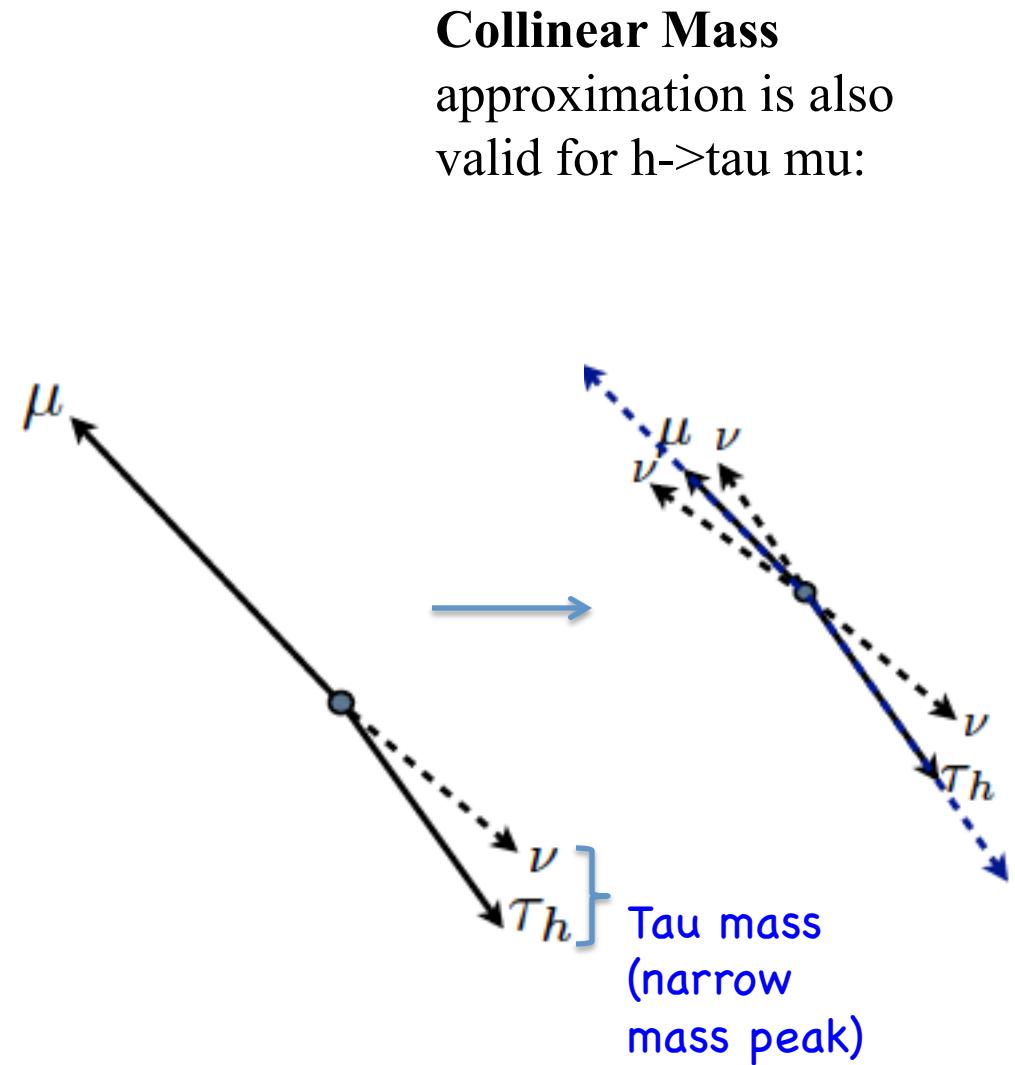
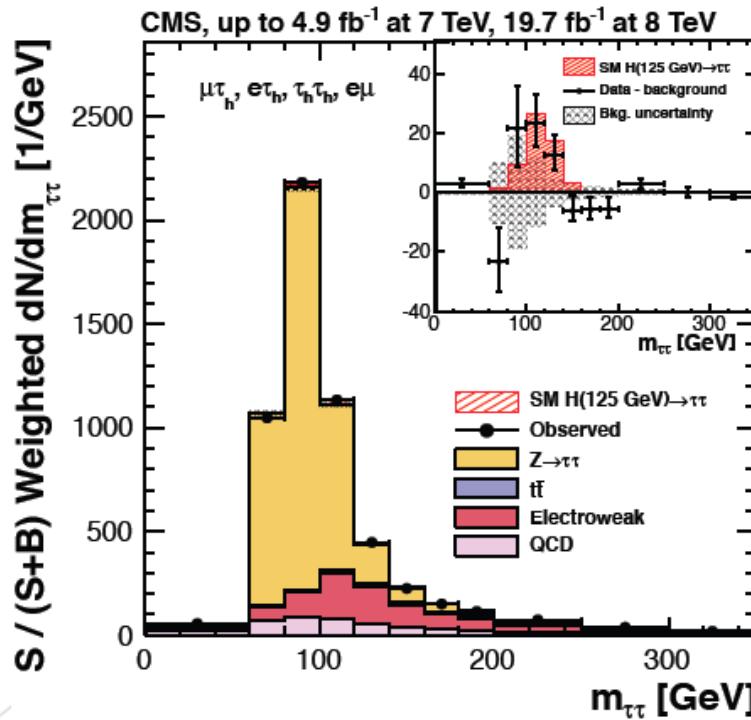
Events / 10 GeV

Data/MC

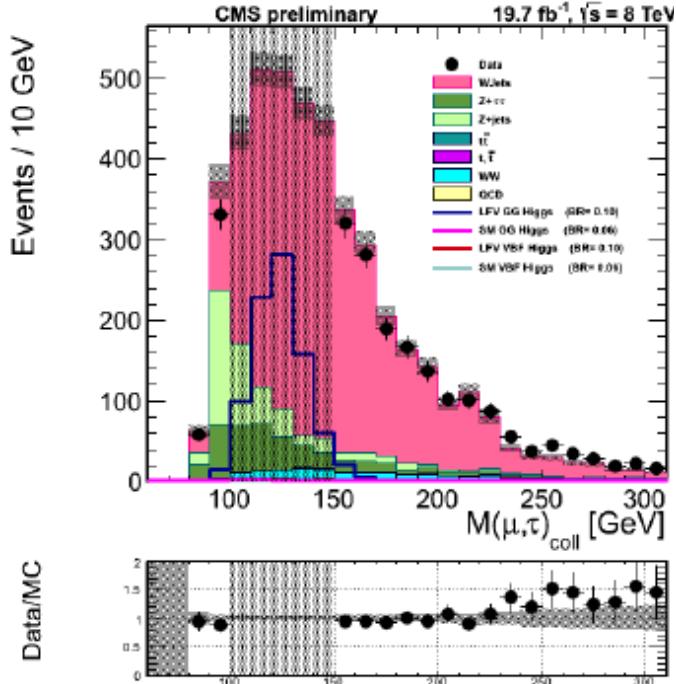
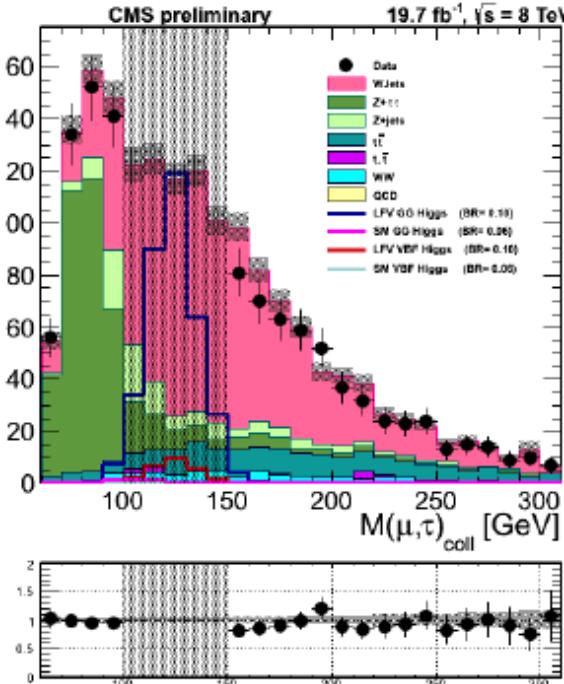
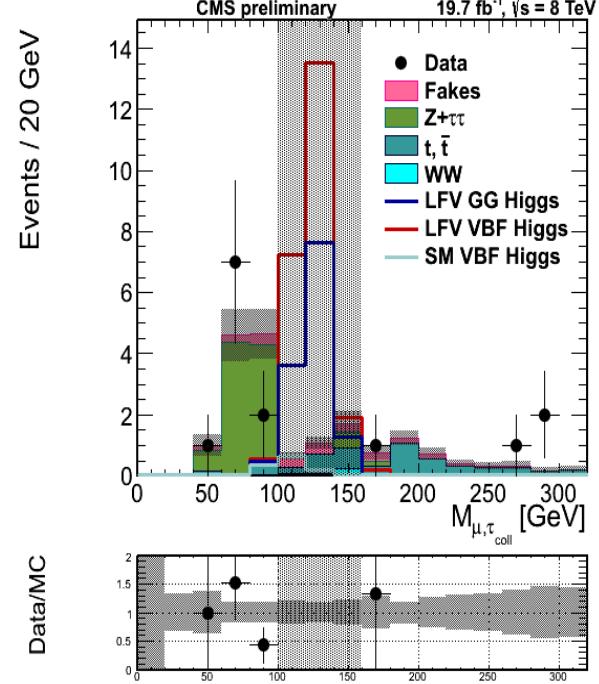


Mass reconstruction

- In ATLAS/CMS when we reconstruct Higgs mass we assume it is $h \rightarrow \tau\tau$



Collinear mass by jet category

0 Jet**1 Jet****2 Jets**

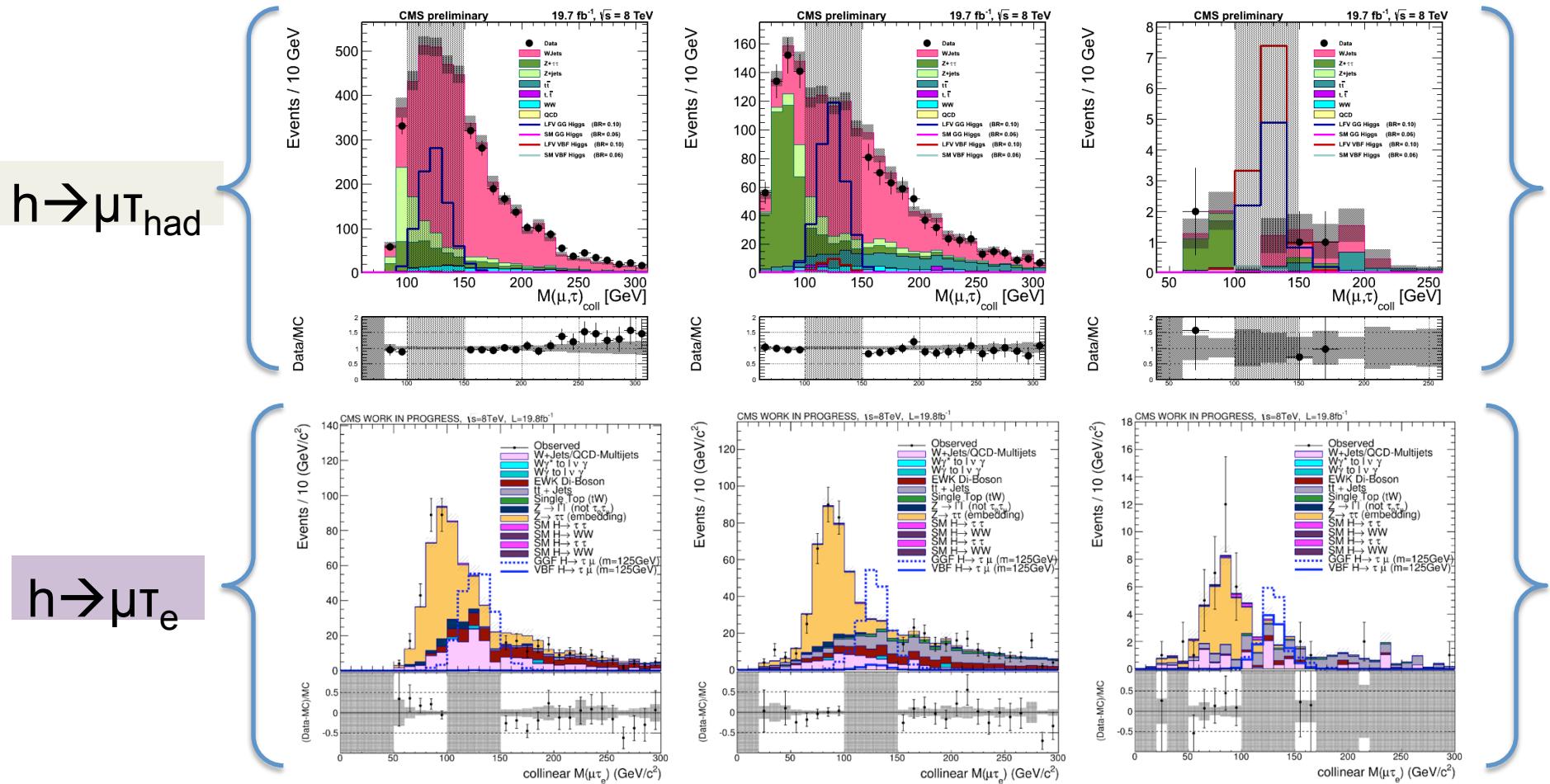
Systematics

Source	Uncertainty
Common uncertainties (Signal+backgr)	
Luminosity	2.6%
Electron Trigger/Id/Iso	3%
Muon Trigger/Id/Iso	2%
Tau efficiency	6%

Background	Uncertainty
Z-> $\tau\tau$ embedding	3%
WJets/QCD Multijet (+fake leptons)	40%
Tau fakes	30%
WW+Jets (MC NLO)	15%
TTbar + Jets	10%
W+y**	100%
Single top	10%
SM Higgs	10%
Theoretical Uncertainties (PDF, Scale..) (preliminary) ~ 10%	

All channels/categories at a glance

- Current expected limit combines the results from the $h \rightarrow \mu\tau_{had}$ and $h \rightarrow \mu\tau_e$ channels, in 3 categories (**0Jets, 1Jet, 2Jets**)
- From this we can obtain a **direct limit on the branching ratio $h \rightarrow \mu\tau$**



	0 Jets	1 Jet	2 Jets	All
μT_e	$Br < 1.8\%$ ($\pm 0.92\%$)	$Br < 1.51\%$ ($\pm 0.77\%$)	$Br < 2.7\%$ ($\pm 1.42\%$)	$Br < 1.12\%$ ($\pm 0.57\%$)
μT_{had}	$Br < 1.51\%$ ($\pm 0.77\%$)	$Br < 1.71\%$ ($\pm 0.87\%$)	$Br < 1.42\%$ ($\pm 0.72\%$)	$Br < 0.83\%$ ($\pm 0.42\%$)
μT	$Br < 1.12\%$ ($\pm 0.57\%$)	$Br < 1.12\%$ ($\pm 0.57\%$)	$Br < 1.22\%$ ($\pm 0.62\%$)	$Br < 0.63\%$ ($\pm 0.32\%$)

$Y_{\mu\tau}$ coupling

[arXiv:1209.1397](https://arxiv.org/abs/1209.1397)

Predicted branching ratios for $h \rightarrow e\mu$, $h \rightarrow e\tau$ and $h \rightarrow \mu\tau$:

$$\text{BR}(h \rightarrow \ell^\alpha \ell^\beta) = \frac{\Gamma(h \rightarrow \ell^\alpha \ell^\beta)}{\Gamma(h \rightarrow \ell^\alpha \ell^\beta) + \Gamma_{\text{SM}}}$$

where $\ell^\alpha, \ell^\beta \approx e, \mu, \tau$ and $\ell^\alpha \neq \ell^\beta$

The decay width :

$$\Gamma(h \rightarrow \ell^\alpha \ell^\beta) = \frac{m_h}{8\pi} (|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2)$$

The SM Higgs width is $\Gamma_{\text{SM}} = 4.1 \text{ TeV}$ for a 125 GeV Higgs boson

Previous experimental bounds

Constraints on flavor violating Higgs coupling ($m_H=125$ and assuming flavor diagonal Yukawa couplings equal to SM values):

$\tau \rightarrow \mu\gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	0.016
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu}^2 + Y_{\mu\tau} ^2}$	$\lesssim 0.25$
{ muon $g - 2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
	$\text{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \dots 1.0$

for magnetic dipole moment – this table can be reinterpreted as
 $\text{Re}(|Y_{\mu\tau} Y_{\tau\mu}|) < 0.065$ at 95% CL

Indirect study, based on a
reinterpretation of the $h \rightarrow \tau \tau$
ATLAS result @ 4.7fb^{-1}

95% C.L. limit	$\text{BR}(h \rightarrow \tau\mu)$	$\sqrt{Y_{\tau\mu}^2 + Y_{\mu\tau}^2}$
expected	28%	0.018
observed	13%	0.011

Expected Limits

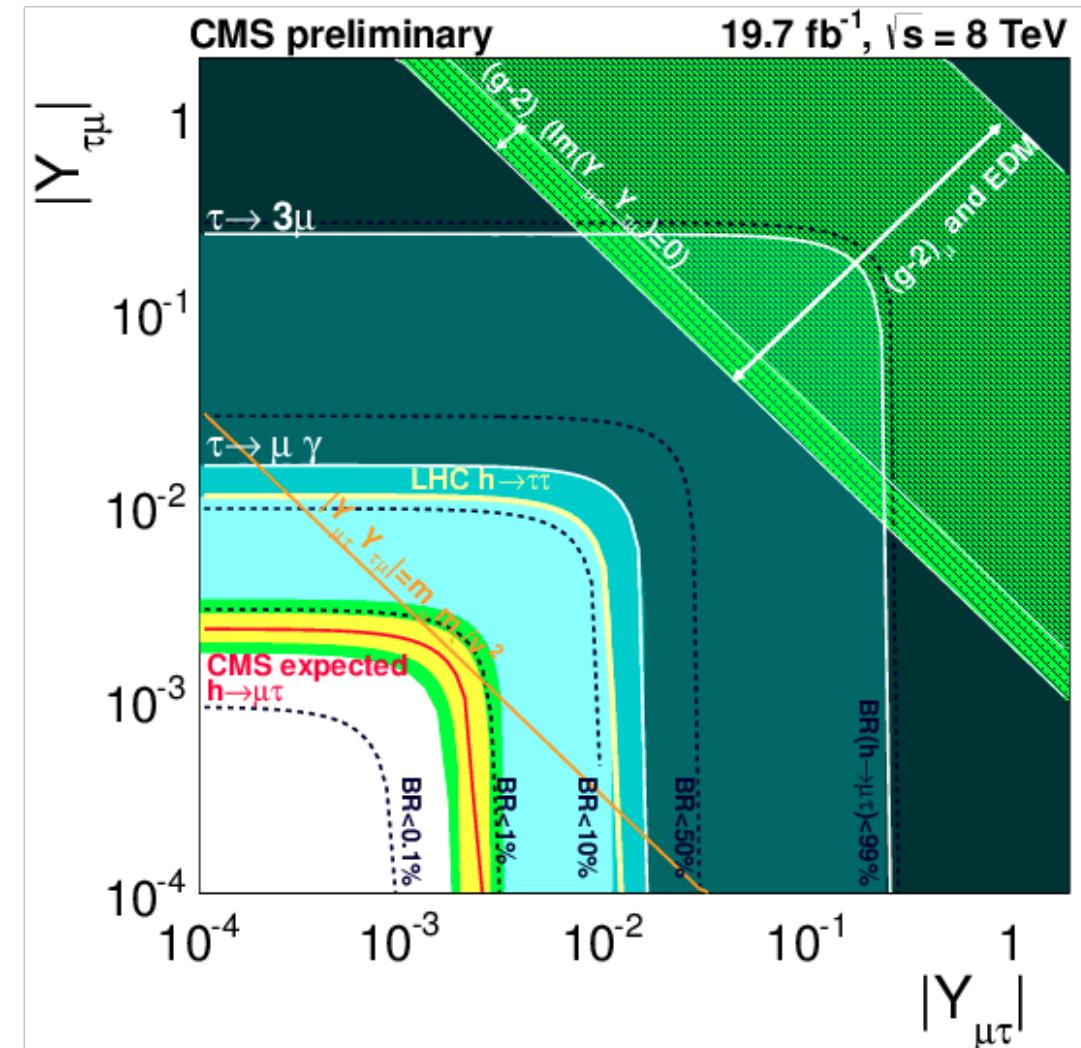
Our expected limit on $\text{BR}(h \rightarrow \mu\tau)$:

BR<0.63+0.32% @ 95% CL

(pending the completion of the systematic studies)

can be reinterpreted as

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 0.0023$$

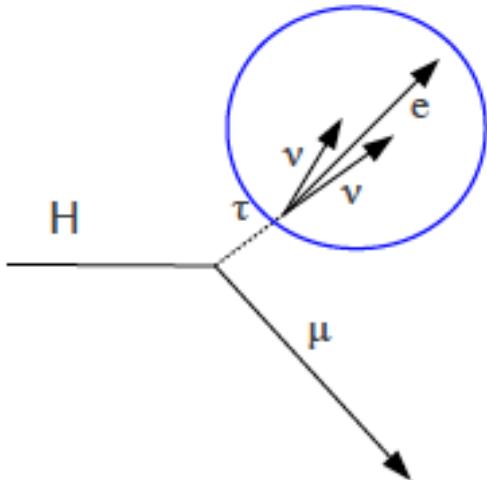


- An expected limit of 0.63% +/- 0.32% has been observed for $\text{BR}(\text{H} \rightarrow \mu\tau)$
- This analysis is well equipped to search for the BSM $\text{H} \rightarrow \mu\tau$ process
- Constraints on flavor violating Yukawa couplings $|\mathcal{Y}_{\mu\tau}|, |\mathcal{Y}_{\tau\mu}|$ are set
- Documentation: Analysis Note ([AN-13-244](#)) is being written
- We are anticipating to finish this analysis in a month's time and going for a pre-approval in February.
- Outstanding tasks include:
 - Shape uncertainty for W+jets
 - Quark-gluon background separation
 - Including SVFIT which shows an improved sensitivity over the collinear mass \rightarrow (already shown by Christian Veelken in Higgs EXO meeting)
 - Optimizing the $\mu\tau_e$ channel
 - Theoretical uncertainties not yet considered

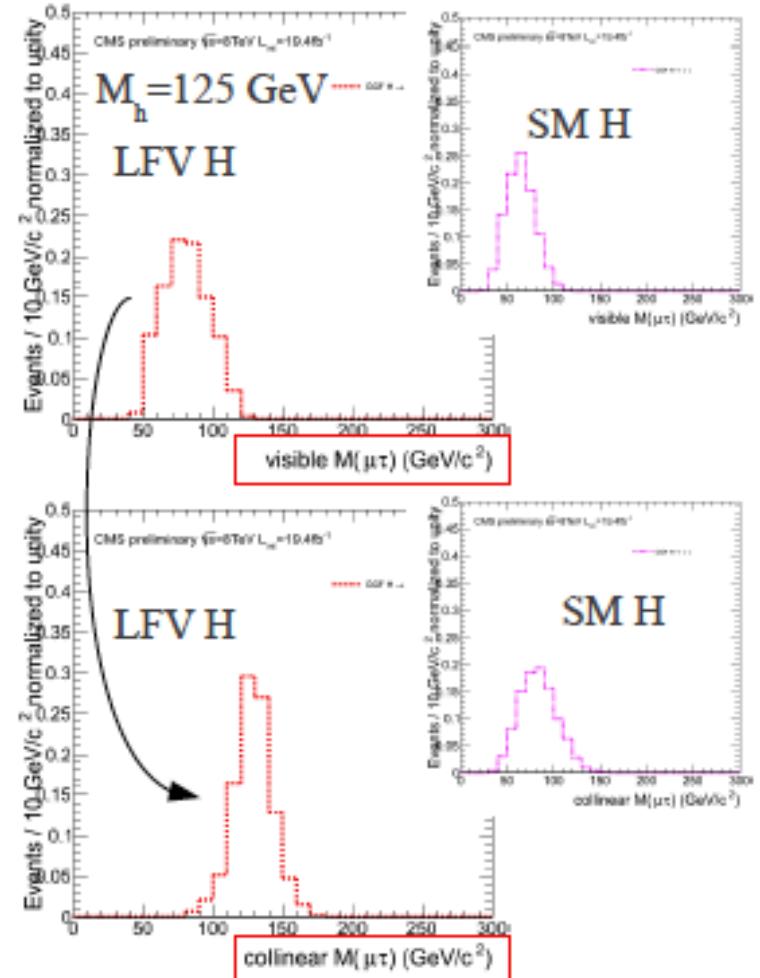
Back up slides

Channel	Coupling	Bound
$\mu \rightarrow e\gamma$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 3.6 \times 10^{-6}$
$\mu \rightarrow 3e$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	< 0.31
electron $g - 2$	$\text{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \dots 0.026$
electron EDM	$ \text{Im}(Y_{e\mu} Y_{\mu e}) $	$< 9.8 \times 10^{-8}$
$\mu \rightarrow e$ conversion	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 4.6 \times 10^{-5}$
$M - \bar{M}$ oscillations	$ Y_{\mu e} + Y_{e\mu}^* $	< 0.079
$\tau \rightarrow e\gamma$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.014
$\tau \rightarrow e\mu\mu$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.66
electron $g - 2$	$\text{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \dots 2.9] \times 10^{-3}$
electron EDM	$ \text{Im}(Y_{e\tau} Y_{\tau e}) $	$< 1.1 \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	$< 1.6 \times 10^{-2}$
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu}^2 + Y_{\mu\tau} ^2}$	< 0.52
muon $g - 2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$ \text{Im}(Y_{\mu\tau} Y_{\tau\mu}) $	$-0.8 \dots 1.0$
$\mu \rightarrow e\gamma$	$(Y_{\tau\mu} Y_{\tau e} ^2 + Y_{\mu\tau} Y_{e\tau} ^2)^{1/4}$	$< 3.4 \times 10^{-4}$

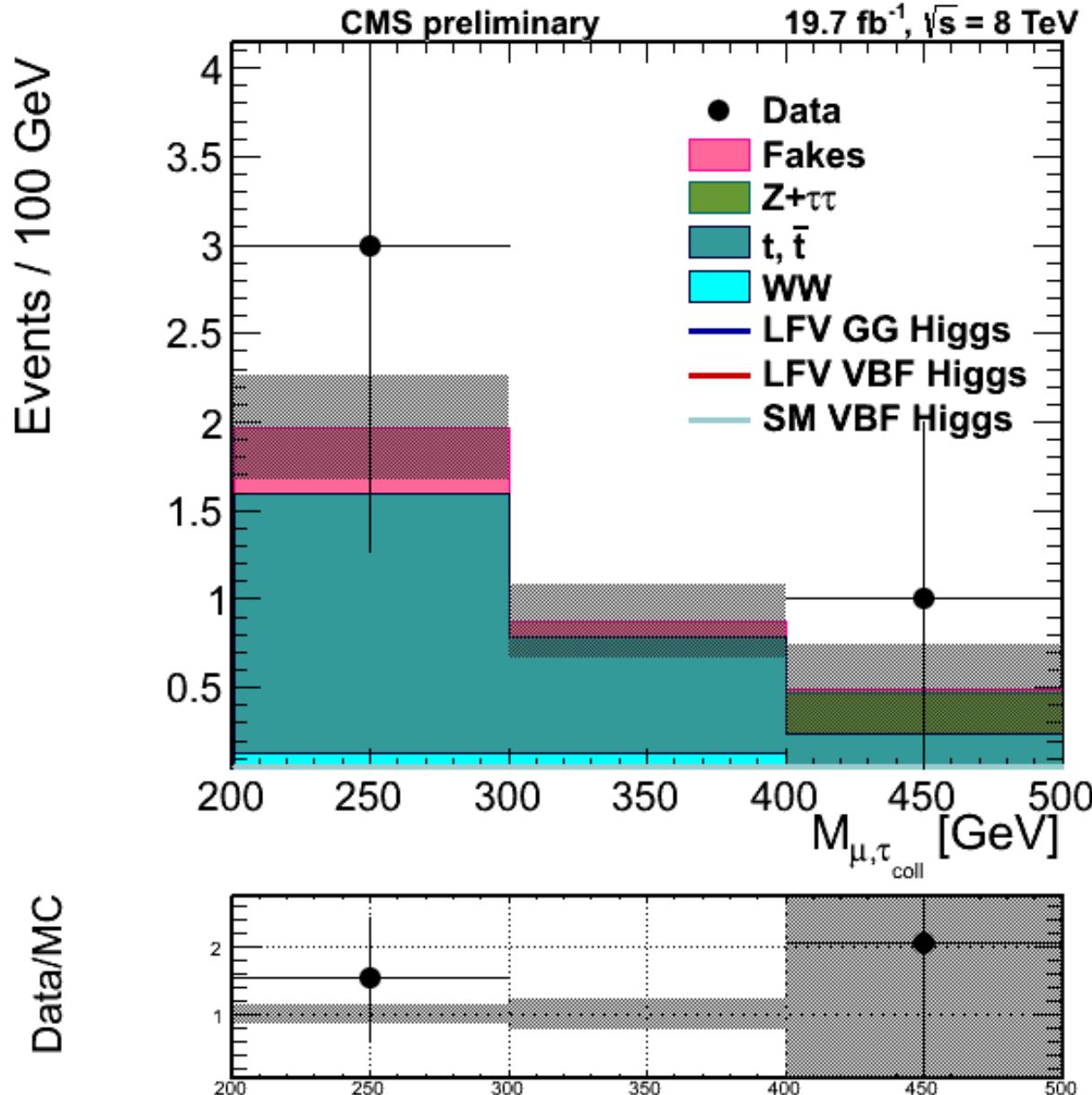
Collinear Approximation

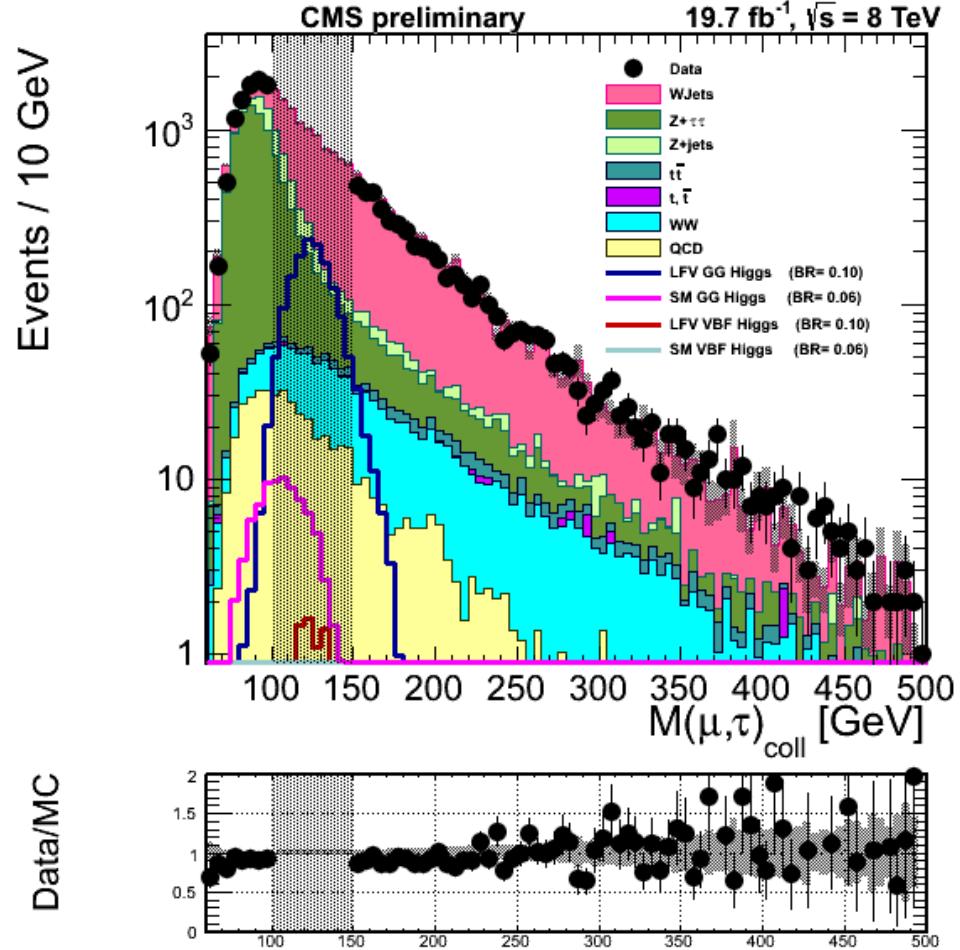
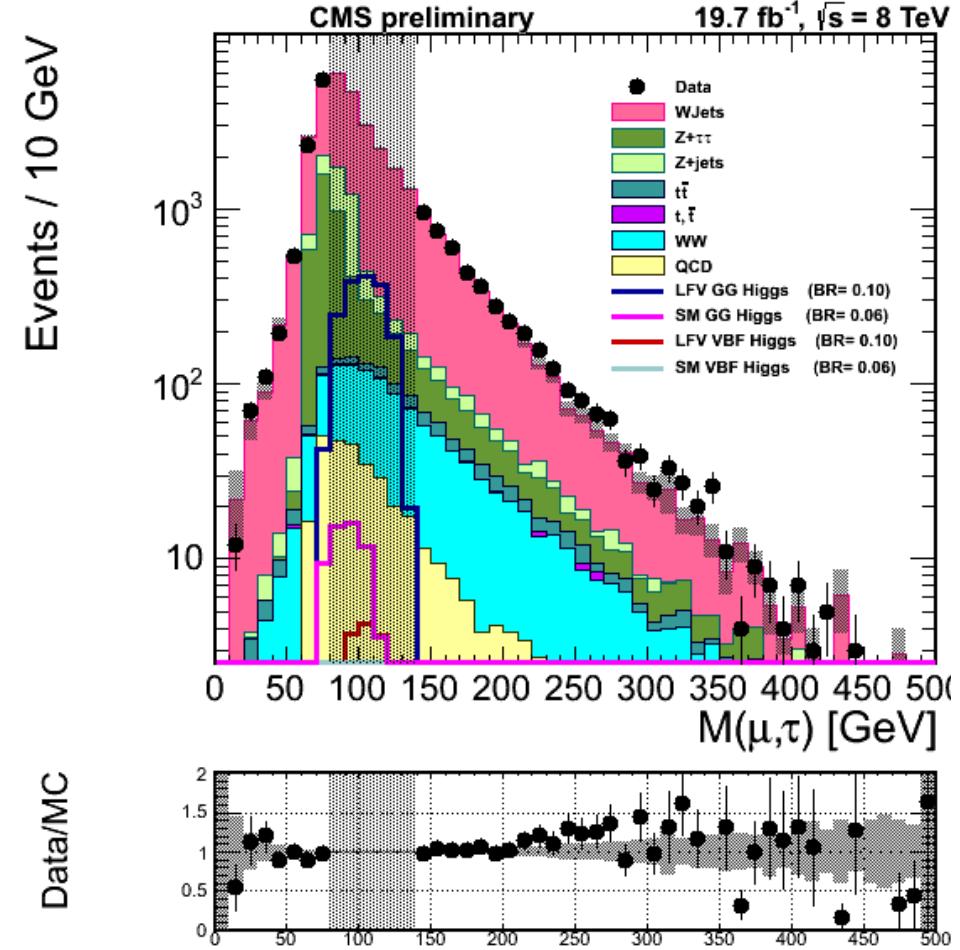


- Assumption: boosted τ decay products are collinear!
- Assumption: MET in the event due to the neutrinos!
- Build neutrino 4-momentum using the MET parallel to the electron
- **Collinear mass: invariant mass of neutrinos+electron+muon**



Tail plot of VBF collinear mass



0-jet: $h \rightarrow \mu \tau_{\text{had}}$ 

Visible mass

Collinear mass